FISHERY ACOUSTIC INDICES FOR ASSESSING ATLANTIC HERRING POPULATIONS

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Abstract

A method for measuring the spatial and temporal distribution of fish school densities and exploitation rates using fishery collected acoustic data and voronoi-natural neighborhood analysis is described. A herring purse seiner fishing on non-spawning feeding aggregations, and a herring gillnetter fishing on smaller, highly dense spawning aggregations, in the southern Gulf of St. Lawrence, Canada, collected acoustic data during regular fishing activity for this study. The relationship between gillnet catch rates (kg/net) estimated for assessment of this stock reached asymptotic values at lower than expected densities and was not useful for tracking daily trends in school density. Gillnet and purse seine catch per metre searched were linearly related to density, and likely are suitable abundance indices for stock assessment estimates. An individual boat with data collected in this manner was found to represent trends in the entire fleet. There was a threshold density beyond which exploitation rates remained low. This threshold provides managers with a method for identifying and eliminating spatial and temporal trends in high exploitation rates and preventing overfishing.

A simulation model calibrated with data from the Pictou 1997 inshore gillnet fishery compared the properties of abundance indices derived from fishery acoustic data to those derived from survey indices. The indices were examined over five fish distribution types ranging from a single spike to a uniform flat distribution, four conditions of fishing and fish movement, and sixteen stock sizes for each of these distribution and conditions. These data are suitable for deriving abundance indices provided the searching covers the entire temporal and spatial distribution of the population.

Fishery acoustic abundance indices provide a basis for adopting a decision rule management paradigm and allowing the metapopulation structure of Atlantic herring to become the basic management unit for this species. These results represent an important alternative to the current $F_{0.1}$ management paradigm for Atlantic herring populations and offer an opportunity to develop a more transparent and responsive management system for the long term viability of Atlantic herring fisheries.

Résumé

Le présent document décrit une méthode utilisée pour mesurer les répartitions spatiale et temporelle des densités de bancs de hareng et les taux d'exploitation en se basant sur des données acoustiques obtenues dans le cadre de la pêche et sur une analyse de voisinage naturel voronoi. Pour les besoins de l'étude, un pêcheur à la senne coulissante pratiquant la pêche dans des concentrations de harengs non encore reproducteurs en phase d'alimentation, ainsi qu'un pêcheur au filet maillant pratiquant la pêche dans des concentrations plus petites mais très denses de harengs adultes, dans le sud du golfe du Saint-Laurent, au Canada, ont recueilli des données acoustiques pendant leurs activités courantes de pêche. Le rapport entre les taux de capture au filet maillant (kg au filet) estimés aux fins de l'évaluation de ce stock a atteint des valeurs asymptotiques à des densités plus faibles que prévu et n'a donc pas été utile pour suivre de près les variations quotidiennes dans la densité des bancs. Les prises au filet maillant et à la senne coulissante obtenues par mètre de zone de recherche avaient une relation linéaire avec la densité; ce sont donc vraisemblablement des indices d'abondance convenables pour évaluer les stocks. On a déterminé que les données recueillies par un bateau en particulier selon cette méthode étaient représentatives de la tendance de toute la flottille. Au-delà d'un certain seuil de densité, les taux d'exploitation sont demeurés faibles. Ce seuil permet aux gestionnaires de cerner et d'éliminer les tendances spatiales et temporelles des taux d'exploitation élevés et d'éviter la surpêche.

En utilisant un modèle de simulation calibré sur des données provenant de la pêche côtière au filet maillant à Pictou en 1997, on a pu comparer les propriétés des indices d'abondance tirés des données acoustiques fournies par les pêcheurs et les propriétés des indices établis à partir des relevés. On a examiné les indices pour cinq types de répartition du poisson, allant de la pointe unique à une ligne régulière, pour quatre conditions de pêche et de déplacement du poisson, et pour seize tailles de stock pour chacun de ces types de répartition et

conditions. Ces données sont appropriées pour construire des indices d'abondance à condition que la recherche vise toute la répartition temporelle et spatiale de la population.

Les indices d'abondance établis à partir des données acoustiques fournies par les pêcheurs servent de base à l'adoption d'un paradigme de gestion basé sur la règle de décision et permettent à la structure des métapopulations du hareng de l'Atlantique de devenir l'unité de gestion de base de cette espèce. Ces résultats représentent un nouveau paradigme de gestion qui pourrait fort bien remplacer le paradigme de gestion actuel basé sur le taux de mortalité $F_{0,1}$ de populations de hareng de l'Atlantique, ce qui permettrait d'élaborer un régime de gestion plus transparent et mieux adapté en vue de la viabilité à long terme de la pêche du hareng dans l'Atlantique.

1. Introduction

A central goal of fisheries stock assessment is to determine if fishing mortality is within conservation targets. Conservation targets may be defined in a number of ways and may be based on a target fishing mortality, life history or ecological characteristics, or both. For example, target fishing mortalities are often defined as a fixed exploitation rate that is not to be exceeded. Management strategies such as $F_{0.1}$, F_{med}, $F_{ext.}$ (Macguire and Mace 1993; Beverton 1998) are examples of fixed exploitation rate targets and management strategies. Life history or ecological targets are often defined as the requirement to maintain the spatial and temporal integrity of spawning components or a specific age structure (Anon 1997). Increasingly, conservation targets are defined by fishing mortality and life history objectives because the spatial and temporal structure of a spawning component will be compromised if all the fishing mortality comes from one area and time, even if the fishing mortality summed over all components is within conservation limits. If, however, the overall fishing mortality is kept within conservation limits and is distributed in proportion to the relative abundance of the various spatial and temporal components, it is expected that the conservation goals would be satisfied. A first step in achieving these goals is to provide managers with tools that would allow them to spatially and temporally distribute fishing mortality relative to the size of the schools being harvested. To meet these targets, information on the spatial and temporal distribution of fish biomass and exploitation rates is required (Claytor and Clay 2001).

This thesis describes a method for measuring the spatial and temporal distribution of fish school densities and exploitation rates. The method was developed using biomass estimates derived from acoustic data collected during regular fishing activity of two fishing fleets in the fall herring fishery in the southern Gulf of St. Lawrence, Canada. The fleets are an inshore gillnet fleet fishing in Pictou, Nova Scotia, Canada and a mid-shore fleet of purse seiners fishing in Chaleur Bay, bordering on Québec and New Brunswick, Canada. The gillnet fleet fishes on fall spawning aggregations during September. The purse seine fleet fishes from August to October on post-spawning feeding and migrating schools of fall and spring spawning herring. A simulation study, based on the Pictou, Nova Scotia inshore fishery, tested the effects of fishing, fish movement, fish abundance, and fish distribution on the ability of acoustic simulated data to provide abundance indices for stock assessments. In this case, an abundance index is defined as an estimate of stock size trends that is proportional over all possible abundance levels and patterns of fishing, movement, and aggregation in the assessed fish stocks. In addition, the relationship between the index and abundance of the stock should be linear with positive slope, and the index should be zero when abundance is zero. Estimates of stock size trends can come from many sources, including fishing captains' opinions, logbooks, and random surveys. These estimates of trends must satisfy the above conditions to qualify as an index.

Providing advice on spatial and temporal trends in fishing mortality minimally requires an abundance index. Even if managers are interested in regulating a fishery by direct control measures such as seasonal timing and effort, rather than quotas based on fixed exploitation rate strategies, some measure of change in stock abundance is required to guide the implementation and assessment of these measures. For this reason, all stock assessment models rely on abundance indices to estimate trends in stock biomass and fishing mortality. Abundance trend estimates and ecological characteristics that are not proportional indicators of stock trends can cause erroneous conclusions regarding fishing effects if they are used as indices of abundance.

Abundance indices typically come from two sources: the fishery, and fishery independent surveys. Fish movement and aggregation patterns create two major difficulties in deriving abundance indices for determining population trends. Changing and non-linear relationships between the abundance trend estimator and stock size is the first of these difficulties and creates an inconsistent bias in stock trend estimates. High variance in an abundance trend estimator is an additional problem because it creates uncertainty in stock size estimates and predictions regarding the effect of management actions.

Pelagic species like herring, capelin, anchoveta, and sardines are particularly prone to these problems. Movement and aggregation patterns of these species often cause the development of changing and non-linear relationships between abundance trend estimators and stock size. Stock size overestimates from these patterns lead to recruitment overfishing caused by undetected high fishing mortalities. Such undetected fishing mortalities caused the collapse and closure of Atlanto-Scandian, North Sea, Celtic Sea, and Georges Bank herring stocks in 1976 and 1977 (Saetersdal 1980). Lengthy recovery times increase the impact of these closures; this impact is evidenced by the Georges Bank herring stock which first began to show signs of recovery in 1987 (Stephenson and Kornfield 1990). Abundance, however, was not sufficient to support a fishery until 1995 (Melvin et al. 1995). Similar collapses and poor recoveries were observed in the Peru anchoveta and California sardine fisheries (Glantz and Thompson 1981).

These problems are often most readily identified when using commercial catch rates for abundance indices, but similar problems can also occur using fishery independent surveys. Research surveys are often restricted to specific areas and times of year and even small changes in migration timing or aggregation patterns may bias results from otherwise robust statistical designs. Survey estimates with large variances and unknown relationships with stock size have resulted from fish movement and aggregation patterns for several pelagic stocks in Atlantic Canada and created difficulties in assessing their stock status (DFO 1996; DFO 1999a,b; Wheeler et al. 1992). These difficulties have lead to criticism of the use of surveys by the fishing industry. The criticism most often voiced by the herring industry in the southern Gulf of St. Lawrence is that the surveys are not conducted during times when they observe large schools of fish. In addition, the size of most research vessels precludes surveys in shallow water and in areas where fishing gear such as lobster traps and gillnets are deployed. These areas are often where the fisheries occur and hence are of most interest to the fishing industry. These factors make it difficult to convince the fishing industry that survey indices are unbiased and accurate enough for fishery management decisions. Consequently, these issues are a major source of conflict in stock assessment and management.

Conflicts over surveys are difficult to resolve because there is often no alternative to government research vessels for surveys. Conflicts over catch rates are difficult to resolve because the fishing industry and stock assessment scientists often have divergent concerns about inconsistencies inherent in using catch rates as abundance indices. For example, scientists are often concerned that catch rates have remained high in spite of population density declines because of efficient search methods available to modern fishing fleets (Hilborn and Walters 1992). Alternatively, concerns among industry are that catch rates have been lowered because of management or market restrictions on daily catches, interference from other gear, and weather (Claytor et al. 1998a).

The danger of collapse, the long recovery periods, the poor performance of survey methods and commercial catch rates as abundance indices, and the high catches of pelagic fisheries in the world (Beddington and Rettig 1984; Corten 1999) make it important to investigate measures for developing alternative abundance indices for these fisheries. Hence, a principal objective of this project is to determine if industry-based data collection can provide indices that are proportional at different levels of movement, aggregation, and abundance in fish stocks.

Assessment of the southern Gulf of St. Lawrence herring stocks has had a long dependence on fishery catch rates as the principal abundance index. The first assessments relied on purse seine catch rates (Winters et al. 1977; Winters 1978; Winters and Moores 1979, 1980: Lett et al. 1978). However, as the gillnet fishery became more important, subsequent assessments relied increasingly on gillnet catch rates (see Cleary 1981; Ahrens 1985; Clay and Chouinard 1986; Chadwick et al. 1989; Claytor and LeBlanc 1999). In addition, assessment advice for this stock has been provided only for the overall spring and fall spawning stocks and not for the local stock components within these seasonal stocks. The provision of overall advice is a concern for industry because sharing the TAC among components is not based on annual trends in estimated size of local spawning components, but on an historical sharing formula based on catch levels and historical data regarding the relative size of the stocks in the mid-1980s. As a result, groups that feel they have taken conservation measures, such as restricting boat daily boat catches and increasing mesh size, feel they are not reaping the relative benefits of those measures. Some industry groups feel penalized for these efforts when the overall TAC declines because stocks in other areas are going down, whereas, they feel their stock is increasing. This leads to conflicts in management of the resource and difficulties in ensuring that fishing mortality is spread equitably amongst the spawning components. As a result, in this fishery (Claytor et al. 1998b) and in many others (Kruse et al. 2001) there is increasing demand for local area assessment and management. In many of these localized areas, including the southern Gulf of St. Lawrence, industry-collected data is the only viable method for collecting the data required for local assessments.

Fishing captains routinely examine the distribution and timing of fish stocks using sounder and sonar information to determine when and where to fish. To take advantage of this behaviour for acquiring assessment information, automated acoustic recording systems were deployed on fishing vessels. The systems are identical to those used during regular acoustic research surveys in the southern Gulf of St. Lawrence except they are completely automated. The fishing vessel captain is only required to turn the system on upon leaving port to begin recording, and off upon returning to port. During the fishing trip, all acoustic data are collected while the boat searches for fish schools, and the data are digitally stored along with position information from a global positioning system (GPS) for later processing.

The historical method for attempting to capture data for abundance indices and fishing distribution patterns has been the use of logbooks. However, logbooks are often not completed or are inaccurately filled out, they provide information on fish abundance only where fishing occurs, and they cannot record the searching behaviour and response of fishing fleets to changes in fish distribution and abundance. Alternatively, the automated acoustic approach provides objective information on the time spent searching for fish and handling the catch, the response of fishing captains to changes in fish abundance, the spatial distribution of fish before and after fishing, the precise location of catches, and the size of schools fished and not fished during regular fishing activity.

To determine the ability of fishery acoustic data to provide viable abundance indices for stock assessment, the following objectives were identified for this research. First, determine an appropriate density estimation method for automated acoustic data. Second, determine the relationship between catch per unit effort, kg/net, and kg/metre of searching on the fishing grounds, and fish density observed by boats collecting acoustic data. Third, determine the spatial and temporal distributions of exploitation rate indices and determine if they would provide managers with the necessary tools for adjusting fishing mortality in these fisheries. Fourth, determine if fish density and catch rates are useful indirect measures of the temporal and spatial distribution of exploitation indices. Fifth, create a variety of models compatible with what is known from the literature and experience from the Pictou gillnet fishery, to study the properties of various proposed stock indices. The rationale for this approach is that a good index should be proportional throughout the range of plausible fish and fishing captains' behaviour.

The investigation concentrates on determining whether or not fishery acoustic data can provide reliable nightly abundance indices. As shown in subsequent chapters, a reliable nightly index of abundance does not exist for southern Gulf of St. Lawrence herring. Concentrating on this objective is consistent with the concept of 'proven reserves' or 'proven production potential' in that the greatest improvements in fisheries management are most often accompanied by improved understanding in population abundance trends (Pearse and Walters 1992). Obtaining abundance indices that are consistent with these concepts allows the investigation of biological and management questions that can be used to develop new management paradigms for southern Gulf of St. Lawrence herring. Among the most important of these would be determining the exposure duration of individuals or groups of herring to exploitation in order to better manage spatial and temporal trends in exploitation rate.

The thesis presentation is organized by chapters. Chapter 2 begins with a background discussion on fishery and fishery independent abundance indices and some of the factors affecting their proportionality and use in assessments. Chapter 3 is a description of the historical and current data and models used to assess herring stock trends in the southern Gulf of St. Lawrence. Chapter 4 contains a discussion on the rationale for area assessments of the southern Gulf of St. Lawrence herring stock. It describes what is known about the stock structure of Atlantic herring in Europe and the southern Gulf of St. Lawrence. The metapopulation model as described by Cooper and Mangel (1999) is provided as a theoretical basis for area assessments of herring stocks. Chapter 5 presents biomass and exploitation rate estimates developed from acoustic data collected during regular fishing activity by the Pictou, Nova Scotia inshore gillnet fleet in 1997 and the Chaleur Bay purse seine fleet in 1995. This analysis indicates that the traditional assessment catch rates are not indices of in-season abundance and exploitation rate trends, catch rates based on catch/metre searched are useful indices, and exploitation rate indices suggest temporal trends that would be useful for distributing fishing mortality in the inshore gillnet fishery. These trends are not as readily identifiable in the purse seine fishery as in the gillnet fishery. The simulation study that tests the method is presented in Chapter 6. The results of this study indicate that density estimates based on acoustic simulated data collected while searching for fish are a useful index, but estimates based on simulated data collections that are terminated when the boat limit is caught quickly are not. Chapter 7 describes a management paradigm, based on the metapopulation structure of herring, that uses decision rules and fishery acoustic indices as nightly measures of 'proven stock'.

2. Background on fishery and survey indices

2.1 Introduction

Abundance indices are required in stock assessments because absolute measures of biomass are usually impossible to obtain. As a result, stock assessment scientists look for indicators that have a consistent relationship with the true size (biomass or numbers) of the stock. When this relationship is consistent over all conditions it fits the definition of an index. It remains an index, regardless of bias or trends, as long as the relationship is predictable, linear, increases with stock size, and is zero when the stock is zero. Occasionally, the relationship between the stock and the index can be determined experimentally, but most often it is estimated using a population or statistical model.

This thesis investigates whether acoustic data collected during regular fishing activity is an abundance index. This investigation is important because there are a number of factors that affect the proportionality of commercial catch rates and research surveys in identifying stock trends that may not affect acoustic data collected during regular fishing activity. Proportionality is the principal assumption in how an index is linked to a population. Failure to meet this assumption can among other things, lead to retrospective patterns which continually over-estimate stock size in the most recent year (Mohn 1999).

Traditional logbook or catch data used in assessments, at best, only collects data where fishing occurs, and at worst is subject to mis-reporting and omissions regarding landings and fishing area. In contrast, the acoustic data collection proposed here is analogous to predator-prey models in which searching and handling time are important indicators of prey abundance (Holling 1959). The proposed acoustic method collects data on searching and handling time, and has the additional advantage of estimating the density of the prey along the searching track. Thus, because these data are expected to provide objective information on catch locations and density of fish throughout the fishing area and not just in catch locations, they may be expected to be an improvement on traditional catch rate (CPUE) indices. In addition, these types of acoustic data can provide data concerning searching and handling patterns and time that are essential for understanding fishing tactics and the predator component of the fishery (Pelletier and Ferraris 2000) and for investigating the relationship between search time and stock size (Mangel and Beder 1985). Alternatively, a random or systematic design does not control the acoustic data collection and the effect this may have on an estimate's consistency is not predictable. The intensity of the data collection may lead to better performance than survey methods in some cases, while the combination of directed and random search may lead to poorer performance in others.

2.2 Fishery catch rates

Catch per unit effort (CPUE) was among the first abundance indices used in fish stock assessments. While catch is usually defined in weight or numbers, effort is defined by the type of fishery. For example, effort could be trawl tows, number of nets, gillnet soak time, number of days fished, or any other appropriate measure of fishing activity determined by a particular fishery. It makes intuitive sense that the amount of effort it takes to catch fish should in some way be related to abundance and for this reason fishery catch rates are used in almost all stock assessments (Hilborn and Walters 1992).

The basic model for using CPUE in stock assessments is a linear relationship between CPUE and biomass defined as:

$$CPUE = qB \tag{1}$$

where B is biomass, and q is a catchability coefficient defined as the proportion of the population captured by a unit of fishing effort, or the probability of capturing a fish (Collie and Sissenwine 1983).

The critical assumptions for this relationship were identified early in stock assessment research. Russel (1931) recognized that sampling must be random for this relationship to hold, that the index would only be good for short periods of time, and that there would be problems with gear standardization. Beverton and Holt (1956) developed an explicit model for the conditions under which CPUE could be used to estimate stock size and fishing mortality. The essential feature was that fishing mortality must be proportional to the vessel's efficiency or fishing power. They identified spatial effects as a major contributor to non-linearity in the index by defining fishing intensity as the fishing effort per unit area and recognizing that concentrating activity in dense areas could increase fishing efficiency. They were among the first to point out that skill gradients and information exchange among skippers could also change the relationship between CPUE and biomass. Most models relating CPUE to biomass still require the proportionality assumption whether they are age-aggregated models of the Schaefer type (Schaefer 1954, 1957; Pella and Tomlinson 1969; Deriso 1980; Schnute 1987) or age-structured models using virtual population analysis (VPA) or forward simulation fitting (Gavaris 1988; Megrey 1989) (Fig. 1).

Fish and fleet dynamics combine to make catchability non-proportional and non-linear with respect to biomass. The distribution of the resource and the way in which harvesters search and react to this distribution determine how catchability will change. For example, catchability may change with respect to growth, time, and density (Swain and Sinclair 1994; Arreguín-Sanchez and Pitcher 1999). Abiotic effects such as temperature may also have important effects (Koeller 1999).

The most likely pattern to develop between CPUE and abundance in finfish fisheries is hyperstability, where CPUE stays high as abundance drops and catchability is inversely related to stock size. In this situation, fish remain concentrated as abundance declines, and because searching is highly efficient, effort is concentrated where fish are abundant (Fig. 1). The classic example is one of fishing on spawning aggregations (Hilborn and Walters 1992) which occurs in the southern Gulf of St. Lawrence herring fishery (Claytor and LeBlanc 1999). In these situations, local area dynamics of searching and handling dictate CPUE because fish are easily found and handling time, hold capacity, and market or management restrictions may limit CPUE. Thus, whenever fish are found in concentrated schools regardless of population size, declines over a wide range of stock sizes are not likely to be detected by an analysis of fishery catch rates (Clark 01982). Additional factors which maintain high catch rates as populations decline include improved technologies (Kimura 1981), skill gradients among skippers (Quinn 1985), and threshold density cut-offs for fishing locations (Gaertner et al. 1999), as originally suggested by Beverton and Holt (1956). These effects are particularly dangerous when there is a threshold effect, such that, declines in CPUE are only detected at very low biomass levels (Clark 1974).

Several authors have tried to incorporate models for changing catchabilities into stock assessment procedures. These include Bannerot and Austin (1983) who modeled CPUE as:

$$CPUE = q_1 B^{(1+q_2)} \qquad (2)$$

where q1 and q2 are parameters to be estimated.
Cooke and Beddington (1984) modeled CPUE in a similar fashion as:

$$CPUE = q_1 B^{q_2} \qquad 3)$$

An approach with origins in predatory-prey ecology, models changes in catchability as a predation process where predators have finite gut capacities, search areas, and searching and handling times (Peterman and Steer (1981).

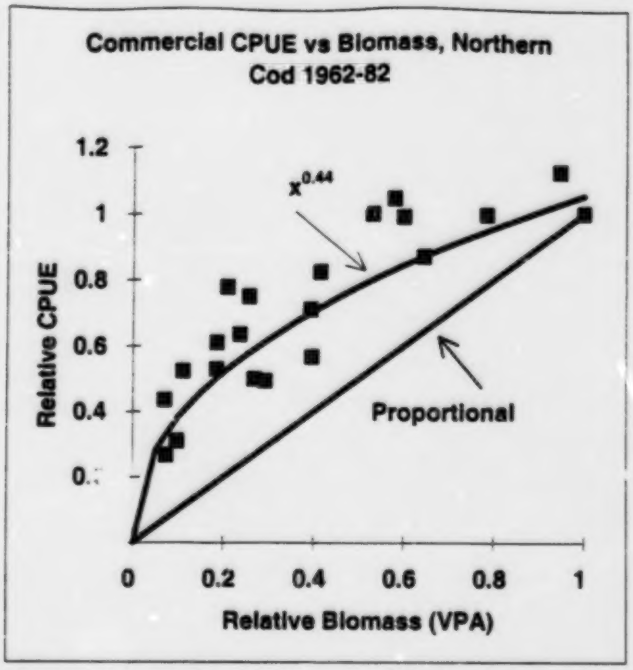


Fig. 1. An example of a hyperstable relationship between CPUE and abundance from the Newfoundland northern cod stock. Analyses assuming a proportional relationship between abundance indicators and stock size will over-estimate biomass when the relationship is truly non-proportional and hyperstable (Walters and Pearse 1996).

Another approach has been to try to allow for change in catchability with density or over time directly in an assessment model (Fournier and Archibald 1982; Archibald et al. 1983). However, these models are prone to over-parameterization (Megrey 1989) and often work well only when catchability is changing systematically over time but not when there are exponential (e.g. q2) effects (Pope and Shepherd 1985). Many of these negative effects on CPUE estimates result from distribution and aggregation patterns and their incorporation into assessment models has been extensively researched (see Kulka et al. 1996 for an example).

2.3 Incorporating distribution and aggregation patterns into CPUE estimates

Reliable abundance indices cannot be expected to be developed by monitoring fishery CPUE without additional information on distribution, movement, and aggregation patterns. In the North Sea herring fishery, increased efficiency of purse seiners caused an increase in fishing mortality (Saville and Bailey 1980). An analysis of catch rates, corrected for the distribution of this stock, showed that fishing mortality was much higher than indicated by an uncorrected catch-at-age analysis. Because a small fleet can exert high fishing pressure, a major effort to estimate stock size independent of the fishery was recommended (Saville and Bailey 1980).

CPUE may also remain high as the area occupied by the stock decreases. As a result, in areas of fishing activity local density may remain the same while overall population numbers and density may decline (Quinn and Deriso 1999). Thus, determining stock area can be expected to make a major improvement in the ability to assess current biomass levels and interpret catch rates (Beddington and Rettig 1984). Cooke (1985) notes that effects on catchability as a stock contracts, can only be assessed by having data on the efficiency of the fleet or area of stock distribution. For example, Misund (1993) found that for mackerel, the school-area to school-biomass relationship from acoustic surveys fit well, however, using purse seine catches produced estimates that were 5 times those of the acoustic survey method.

Several authors have followed the lead of Paloheimo and Dickie (1964) and directly modelled changes in catchability with respect to area effects as:

$$q = q\frac{a}{A} \qquad 4)$$

where a is the area swept by the gear and A is the area occupied by the stock (Pope and Garrod 1975; Houghton and Flatman 1981; Saville and Bailey 1980; Cook and Armstrong 1985).

This approach was also taken by Winters and Wheeler (1985) who demonstrated that catchability was inversely related to area for herring in Atlantic Canada,

$$q = CA^{-b} \qquad (5)$$

where C is the catch and A is the stock area.

Rose and Leggett (1991) found that catchability was inversely related to biomass and stock range for cod. They developed an empirical relationship of

$$q = q_1 R^{-q_2} \qquad 6)$$

where R is the percent of the range covered.

In addition to area coverage, Petitgas and Levenez (1996) tested sea-bottom depth as a covariate in CPUE models. In an investigation of echo types related to sea-bottom and diel cycle, they found that the average number of clusters in an area remained constant. It was found that reduction in the area was not congruent with reduction in biomass, and therefore, low biomass was not confined to a specific and reduced area. As a result, they found that an increase in catchability with a decrease in biomass level was not compatible with their results.

Petitgas (1998) determined that, if the way the fleet samples the density of fish in an area is not altered as density changes, then CPUE data can be used to construct time series indices that are proportional to fish densities. However, if vessel captains begin to co-operate as density drops, the CPUE will no longer be proportional to density but will be higher than model predictions from data collected at higher densities. Many others have noted the requirement for fishing boats to distribute themselves randomly or uniformly with respect to the fishing area (Beverton and Holt 1957; Ricker 1975; Hilborn and Walters 1992; Quinn and Deriso 1999) for CPUE to be used as an index. These requirements and the effects described above restrict the possibilities for using commercial catch and effort data to estimate catchability (Schnute 1983; Miller and Mohn 1993; Gould and Pollock 1997; Gould et al. 1997,1999).

2.4 Survey Indices

Obtaining indices from fishery independent survey estimates has been a common recommendation with respect to the tendency for CPUE to be high even when stock size is reduced (Beddington and Rettig 1984; Saetersdal 1980; Ulltang 1980; Troadec et al. 1980; Anthony and Waring 1980). In addition, many authors suggest that additional information for interpreting and making CPUE an index can only come from surveys (Gillis et al. 1993; Pope and Shepherd 1982; Bannerot and Austin 1983; Richards and Schnute 1986, 1992). Surveys on the other hand are able to quantify trends in recruitment and stock trends independent of mis-reporting problems (Cook 1997). For example, Namibian pilchard and California sardine and mackerel stocks declined when fishing mortality reached a value about equal to the estimated natural mortality. Surveys were identified as the only means to provide the timely data needed for management (Troadec et al. 1980).

Surveys or 'swept-area' methods (Hilborn and Walters 1992, Quinn and Deriso 1999) have as their goal the production of indices by standardizing many of the variables that make CPUE difficult to use as an index. In addition to variables particular to CPUE such as vessel power, gear changes, and effort thresholds, surveys attempt to standardize area and fish distribution effects by consistently collecting data over the same time period and area for each survey.

2.5 Increasing precision - reducing variance

The requirement for random or uniform distribution of effort in surveys is usually met by following a random or systematic survey design. A number of survey types with these designs are used in fishery stock assessments and include random allocation of trawl tows (Doubleday 1981), while acoustic surveys generally use a random or systematic transect design (Simmonds et al. 1991). The use of multistage sampling, of which adaptive sampling is an example, (Thompson et al. 1992; Thompson and Seber 1994) is increasing in use. In these designs the sampling regime is altered as information on distribution and abundance is gathered during the survey (Cairns et al. 1993; Woodby 1998).

Simmonds and Fryer (1996) showed that if the objective of a survey is to determine a precise estimate and if there is positive spatial autocorrelation, then a systematic survey with a geostatistical estimator is preferred over a simple random transect design. The precision is greatest if sampling intensity is greater than the scale of the autocorrelation. Results from systematic surveys, with a centered start, are biased if fish are located preferentially and therefore a systematic random strategy is often preferable. However, if the objective is to obtain an estimate of variance, then a stratified random survey with at least two transects per stratum is preferred.

While unbiased estimators result from random designs, large variances often preclude their use as an index. One method often used to reduce variance in survey estimates is to incorporate covariates such as temperature, depth, or bottom type into the model (Smith 1990; Smith and Robert 1998; Sullivan 1991; Orlowski 1999). Modifications of survey design based on historical abundance are another strategy used to reduce survey variance (Smith and Gavaris 1993). Acoustic surveys require biological samples from trawls or other sampling methods. The collection of these samples needs to be controlled for the additional variance that can be introduced if sampling is inadequate (Godø et al. 1998).

2.6 Fish distribution effects

Inconsistency in survey estimates with respect to true biomass can also result from density-dependent and distribution effects in a manner similar to CPUE. Fish distribution in the water column, diel variation, and reaction to vessels affect the consistency of acoustic and trawl tow estimates (Aglen 1996; Michalsen et al. 1996). Aglen et al. (1999) in comparing trawl and acoustic biomass estimates found that small fish had higher swept area estimates during the day compared to the night, while the trend was opposite for acoustic estimates of juvenile groundfish. For pelagics, they found that considerable amounts of fish were unavailable to the trawl, and that catchability changed between day and night. Others have found similar results, with the general conclusion that catchability varies with depth, time of day, bottom type, and fish density (Somerton et al. 1999), even though the transition time of the diurnal cycle has been found to be <1 hour (Fréon et al. 1993).

Low density of fish ahead of trawls has been found to be associated with low catchability, while high densities have been associated with high catchabilties (Godø et al. 1999). Effects such as those associated with vertical herding, in which fish tend to dive as the boat passes over them ahead of the trawl, horizontal herding, in which fish avoid the wings, and escapement, in which fish attempt to dive under the footrope have led to attempts to experimentally estimate catchability. For example, vertical herding can be estimated by independently using a buoy or by comparing bottom trawl and acoustic estimates. Horizontal herding can be estimated by changing bridles or sweep length, and escapement under the footrope can be estimated using auxiliary bags under the net (Aglen 1996; Somerton et al. 1999).

Density-dependent spatial patterns have been found for groundfish in the southern Gulf of St. Lawrence and results suggest that catchability of these fish increases as density decreases (Swain and Wade 1993). When aggregations are highly dense, values in the tails of distribution can be many times those of the next highest values. In these situations, high values are unrelated to those around them, the high values are rare and the contribution they should make to the stock estimate is uncertain. Thus, high variances occur in the estimates. Adaptive survey designs may reduce variance in these situations (Murray 1996).

The spatial structure of the school can also be used for designing surveys. For example, estimates from kriging are improved if the inter-transect distance is kept smaller than the variogram range for several different types of distributions (Petitgas and Levenez 1996). High densities in small areas are one of the most difficult situations for surveys because the probability of intersecting the school decreases as density and aggregation increase. This difficulty in intersecting the school leads to sampling distributions with relatively large fluctuations in the tails of the distribution. The contribution of these high-density values to the overall biomass is often unknown because areas of intermediate density are not crossed when moving from low to high density. As a result, high densities are often independent and need to be mapped and estimated separately (Petitgas 1993). Petitgas (1993) used disjunctive kriging to analyze highly dense populations of herring sampled using acoustic surveys. This technique divides the highly aggregated distributions into separate data sets for analysis. Simard et al. (1993) found that similar breaks occurred with respect to depth at high density. School area is also affected by swimming speed, and the formation and disappearance of empty areas within schools (Misund 1993).

The occurrence of high variance when biomass is concentrated in a few schools leads to major difficulties in estimating the abundance of pelagic fish stocks. The difficulties in modeling the histogram of the biomass per school led Marchal and Petitgas (1993) to consider estimating the number of schools, which appeared to be much less erratic.

Seasonal distribution changes also affect catchability. For example, anchoveta in northern Chilean waters generally have a broad distribution in winter, but are more aggregated in spring and summer when they are pushed toward the coast (Castillo et al. 1996). Seasonal and within seasonal temperature changes have also been shown to affect distributions by sex, size, and density for groundfish (Swain 1997; Swain et al. 1998). For example, cod occupy colder water than usual at high levels of abundance (Swain 1999). However, not all species change their distribution as abundance changes. For example, American plaice (Hippoglossoides platessoides) have not changed their distribution pattern over five-fold changes in abundance. This lack of change may result from mosaics of habitat patterns within the stock area (Swain and Morin 1996). Consideration of distribution and area effects is as important for surveys as it is for CPUE estimates (Simard et al. 1992; Rose 1992; Misund 1993).

In addition to these broad scale distribution effects, small-scale distributions, such as anisotropy, also affect survey catchabilities. Anisotropy occurs when the spatial correlation among the data points depends not only on the distance between points but also on the direction (Cressie 1991). Kalikhman and Ostrovsky (1997) found that when the distribution is known a priori, surveys in the direction of anisotropy allow better reconstruction of the distribution than do perpendicular transects. Surveys on moving patches, when the patch is smaller than survey area, are improved if the survey is in the direction of movement. If the patch is larger than the survey area, the survey is improved by surveying in the opposite direction.

2.7 Summary

Distribution, movement, and aggregation are the principal reasons for non-proportional relationships between CPUE and survey estimates with true stock size. The CPUE and survey models described above are generally used to estimate total stock biomass and provide advice on fishing levels for the next year. These estimates depend on time trends and consistent catchability relationships to estimate biomass. Data for these models accumulate slowly and when catchability is not proportional, or when management strategies reduce variability, trends are difficult to interpret and fishing level projections are not accurate (Beddington and Rettig 1984; Gulland 1977; Pope 1980; Pope and Shepherd 1982; Pope and Shepherd 1985; Ludwig and Walters 1985).

In the southern Gulf of St. Lawrence fishing occurs on feeding schools which have dynamic movement patterns (Pitcher et al. 1996), and spawning aggregations which are highly clustered (Trevorrow and Claytor 1998). As described above, these movement and aggregation effects have led to inconsistencies between CPUE and survey estimates and true biomass in many areas. The current assessment methodology for southern Gulf of St. Lawrence herring, reviewed in the next chapter, relies principally on CPUE estimators (Claytor and LeBlanc 1999). Although acoustic survey estimates were used as a second index in the most recent assessment of spring spawners, they are not applicable to estimating biomass in localized areas (DFO 2000). Acoustic survey estimates of fall spawners are not internally consistent and have not been used to assess southern Gulf of St. Lawrence fall spawning herring (DFO 2000). As a result, indices based on data other than CPUE and survey data may be required to meet the management goal of distributing fishing mortality equitably among and within stock components in the southern Gulf of St. Lawrence.

3. Assessment background for southern Gulf of St. Lawrence herring

3.1 Stock area

The stock area for southern Gulf of St. Lawrence, Canada herring is the area extending from the north shore of the Gaspé Peninsula, Québec, to the northern tip of Cape Breton Island, Nova Scotia and includes the Magdalen Islands (Fig. 2). This area is consistent with the Northwest Atlantic Fisheries Organization (NAFO) Division 4T, and for quota allocation purposes is divided into management zones that correspond to spawning aggregations and local fishing fleet areas (Fig. 2). Adults overwinter off the east coast of Cape Breton in NAFO Division 4Vn and this region is included in the stock area and the assessment of southern Gulf of St. Lawrence herring.

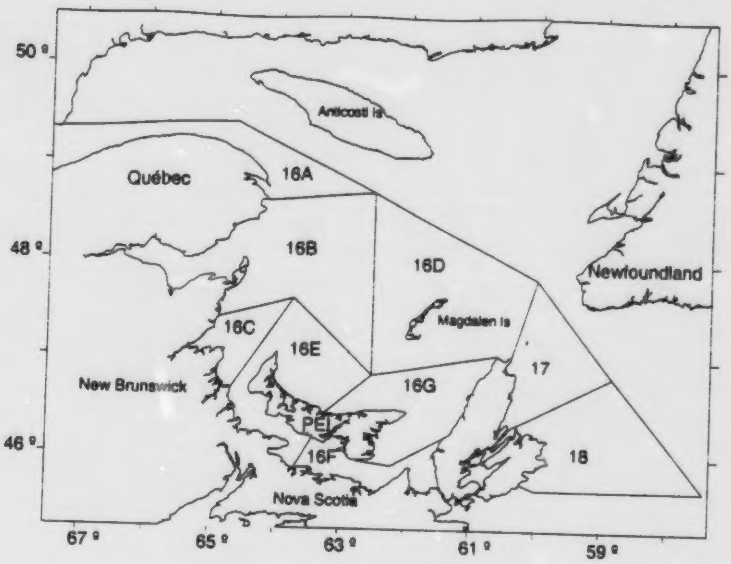
The two seasonal herring spawning components that are assessed for the southern Gulf of St. Lawrence are spring spawners and fall spawners. The assessment for these herring currently provides an F 0.1 fishing level calculation for each seasonal spawning stock. In general, this level has been used to set the total allowable catch (TAC). The population model used to estimate this level is a virtual population analysis (VPA) based on the ADAPT framework (Gavaris 1988). Catch rates are used to calibrate the fall spawner population model, and catch rates and an acoustic survey are used to calibrate the spring spawner population model.

3.2 Migration

Southern Gulf of St. Lawrence spring and fall spawning herring both over-winter in NAFO Division 4Vn. When the ice breaks up in the spring both spawning groups begin to return to the southern Gulf of St. Lawrence. Spring spawners migrate to spawning areas and peak spawning occurs during April and May in various areas of the southern Gulf at depths of < 10m (Fig. 3). After spawning, the spring spawners migrate to Chaleur Bay and northern Prince Edward Island.

Fall spawners remain widely distributed throughout the Gulf from June to September. In the fall, they migrate to spawning areas where peak spawning occurs during September at depths from 5 to 20m (Fig. 3). Large concentrations of pre- and post-spawning fall spawners are observed in Chaleur Bay and north of Prince Edward Island during September and October research surveys. As a result, during the fall of the year, mixtures of spring and fall spawners occur in these areas. By mid-October migration to the over-wintering area has begun and is generally well underway by the 1 November (Claytor 2000). During January, herring are found at depths greater than 80 m in the 4Vn area (Claytor 2000). Juvenile herring (age 2 and less) possess anti-freeze proteins and remain in the southern Gulf for the winter, or at least migrate to 4Vn later than the adults (Chadwick et al. 1990).

Tagging studies conducted in 1970-1971 indicate that southern Newfoundland was also an over-wintering area for this stock during that period (Winters 1977; Winters and Beckett 1978). The tagging returns indicated that beginning in April there was a westward movement of herring into the southern Gulf of St. Lawrence and towards the Magdalen Islands. In October and November they migrated back to southern Newfoundland (Winters and Beckett 1978). Few herring have been observed in this area since the early 1980s when the stock was reduced to very low levels by over-fishing.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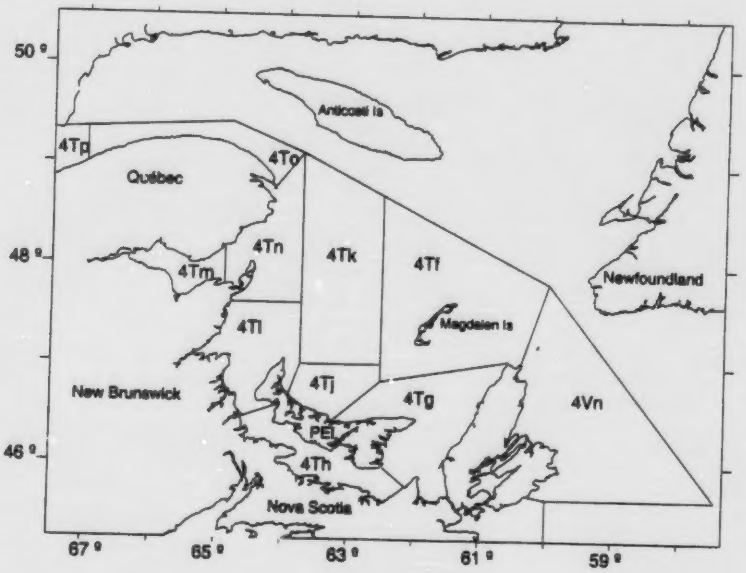
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Nova Scotia

Fig. 2. Southern Gulf of St. Lawrence herring management zones (upper) and Canadian Statistical unit areas (lower) in Northwest Atlantic Fisheries Organization (NAFO) Division 4T.

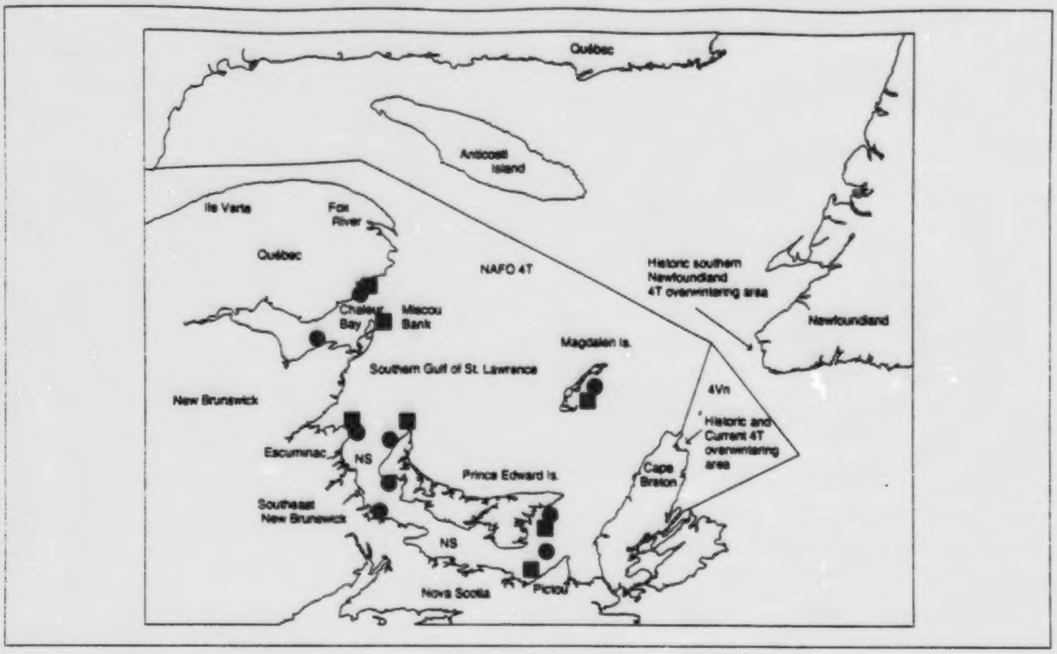

Québec
Anticosti Island
Ile Verte
Fox River
Québec
NAFO 4T
Historic southern Newfoundland 4T overwintering area
Newfoundland
Chaleur Bay
Miscou Bank
Magdalen Is.
Southern Gulf of St. Lawrence
New Brunswick
4Vn
Historic and Current 4T overwintering area
Escuminac
NS
Prince Edward Is.
Cape Breton
Southeast New Brunswick
NS
Nova Scotia
Pictou

Fig. 3. Spring and fall herring spawning areas in the southern Gulf of St. Lawrence. Squares represent fall spawning areas, circles spring spawning areas. Historic and current overwintering areas are indicated. NS; Northumberland Strait.

3.3 Seasonal stocks - Spawning areas

The largest spring spawning populations are in the Northumberland Strait between New Brunswick and Prince Edward Island, followed by the Magdalen Islands. Relatively small spring spawning populations occur in Chaleur Bay (New Brunswick-Québec), eastern Prince Edward Island, and Pictou, Nova Scotia (Fig. 3). The largest fall spawning population is in Chaleur Bay. Smaller fall populations are found in the Northumberland Strait between New Brunswick and Prince Edward Island, eastern Prince Edward Island, Pictou, Nova Scotia, and the Magdalen Islands (Fig. 3) (Claytor and LeBlanc 1999). First spawning for both seasonal components occurs primarily at age 4 but 50% of age 3 herring sampled on 4T fall spawning grounds are in spawning condition.

3.4 Fishery - TAC and quota allocations

Southern Gulf of St. Lawrence herring are harvested by an inshore, primarily gillnet fleet, fishing in 4T and a purse seine fleet of six vessels (>65') in 4T and 4Vn. Five small seiners (<65') also participate in the inshore fishery. Unless specifically stated as small seiners, the terms purse seiners or seiners refer to the purse seine fleet with vessels > 65'. During the spring and fall fishing seasons, seiners are prohibited from fishing in several areas set aside for exclusive fishing by the inshore fleet (Claytor et al 1997).

Prior to 1967, southern Gulf of St. Lawrence herring were exploited mainly by gillnets, and average landings from 1935 to 1966 were 34,000 tonnes. In the mid 1960s, a purse seine fishery was introduced and average landings were 166,000 tonnes from 1967 to 1972. Quotas were introduced in 1972 at 166,000 tonnes and reduced to 40,000 tonnes in 1973 (Fig. 4). The purse seine fleet accounted for most of the catch from the time of its introduction until 1981.

Beginning in 1981, a change in the management plan altered the relative allocation of the TAC between the inshore and purse seine fleets (Fig. 5). The purse seine fleet was allocated 20% of the TAC within the southern Gulf of St. Lawrence plus approximately 4,000 tonnes from the over-wintering area off Cape Breton. In 1992, the Cape Breton portion of the allocation was formally recognized as part of the southern Gulf TAC. The allocation split since 1992 has been 23% to the purse seine fleet and 77% to the inshore fleet (Claytor 2000).

Separate quotas for spring and fall spawners began in 1985. Separate quotas by management zone (Fig. 2) for the fall inshore fleet began in 1987 and for the spring inshore fleet in 1998. Catches of spring and fall spawners combined have been below the TAC since 1988 (Fig. 4).

These quota allocations, to simplify fishery management, are made on a seasonal, rather than spawning group basis. The seasonal allocation is a practical consideration because purse seiners harvest both spawning groups throughout the year, while the inshore fleet harvests primarily spring spawners in the spring, and fall spawners in the fall. The assessment of the fishery and management is based on spawning group. The spring season extends from January 1 to June 30 and the fall season from July 1 to December 31.

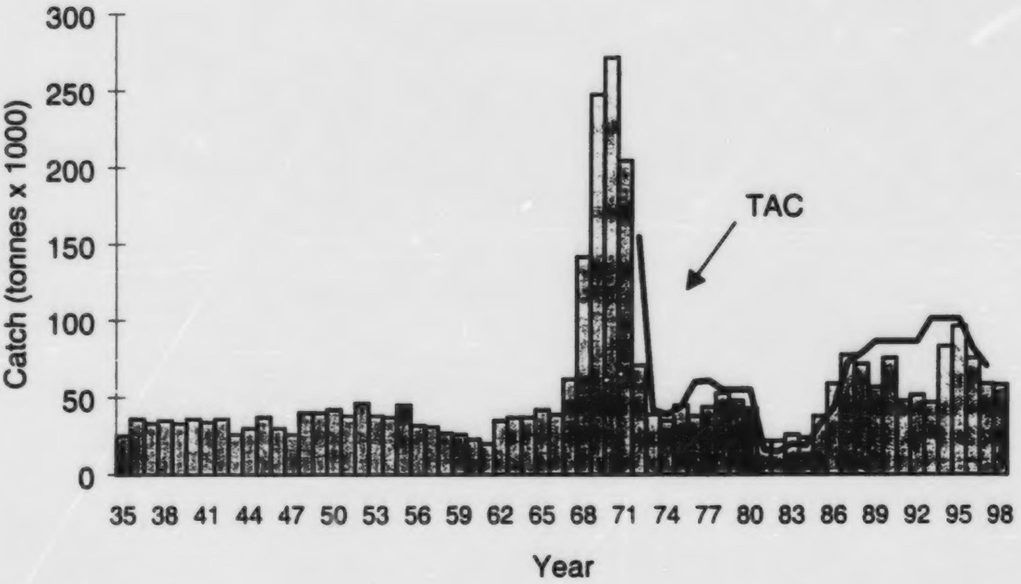


Fig. 4. Combined catch of spring and fall spawning herring in the southern Gulf of St. Lawrence, excluding those caught in eastern Cape Breton (4Vn), compared to overall TAC from 1935 to 1998.

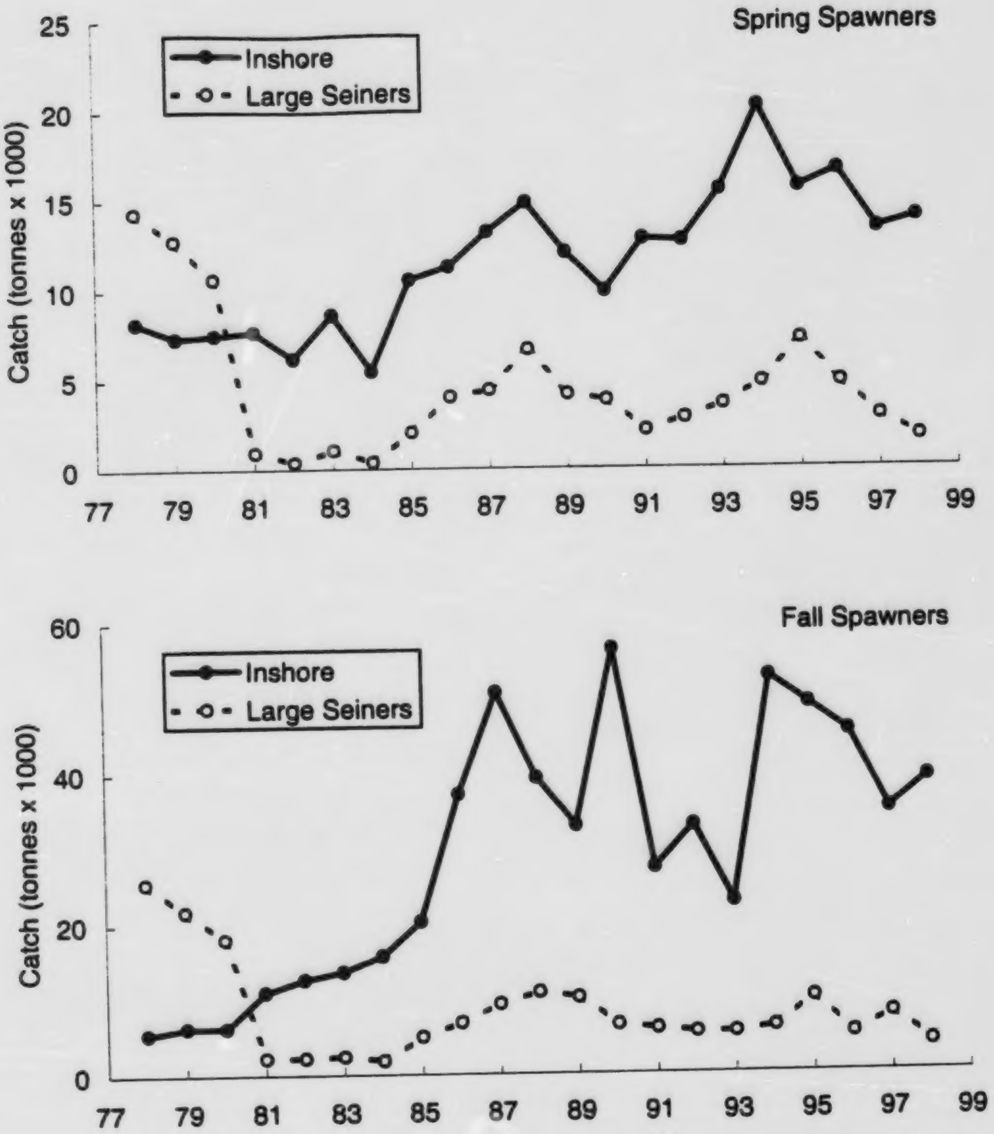


Fig. 5. Change in percentage of catch by gillnet and purse seine fleets in the southern Gulf of St. Lawrence. Prior to 1981 the seiners were allocated 77% of the TAC. Beginninng in 1981, 77% of the TAC was allocated to the inshore gillnetters.

3.5 Fishery - Spring and fall spawner composition

Since 1978, fall spawners have comprised about 75% of the total catch in the southern Gulf of St. Lawrence. Spring and fall spawners are harvested by purse seiners during their spring fishery which occurs just east of the Magdalen Islands or along the Gulf of St. Lawrence coast of northern Cape Breton (Fig. 3). Spring spawners are harvested by purse seiners during their fall fishery in Chaleur Bay and in the over-wintering 4Vn area off the east coast of Cape Breton. The proportion of spring spawners caught in these fisheries has been relatively consistent during recent years and 1998 values are typical (Table 1). The inshore gillnet fleet harvests >97% spring spawners during their spring fishery which occurs on or near spawning grounds. Less than 1% of spring spawners are caught during the inshore fall fishery, which occurs almost exclusively on spawning aggregations.

Inshore fleets are based in their local areas and the number of boats in each fleet is more a function of the fishing community population size than of available biomass. The purse seine fleet is based in northern New Brunswick. Five seiners from western Newfoundland also have historical access to the southern Gulf of St. Lawrence but this access is rarely used.

Table 1. Percentage of spring and fall spawners caught by season and gear type for 1998.

		Spawning Group	
Season	Gear	Spring %	Fall %
Spring	Inshore	99	1
	Seiner	76	24
Fall	Inshore	1	99
	Seiner	21	79
4Vn OverWinter	Seiner	6	94

The dominance of fall spawners in the present day is a considerable change from the 1940s, when 90% of the catch was made up of mature fish from spawning concentrations in May and June. Most of these catches came from the same areas as today, the Magdalen Islands and the New Brunswick portion of the Northumberland Strait. The fall inshore fishery was very small and only occurred around Cape Breton and there was no fall fishery in New Brunswick, Northumberland Strait because it would have been coincident with an established lobster season (Day 1957b). At the present time there is no fall fishery along the Gulf shore of Cape Breton. The New Brunswick, Northumberland Strait fall inshore fishery accounts for about 15% of the landings in this fishery and about 80% of the spring fishery landings (Table 2). In the New Brunswick, Northumberland Strait fishery today, those fishing lobster in the spring, fish herring in the fall, and those fishing herring in the spring fish lobster in the fall.

In the Chaleur and Gaspé areas of the southern Gulf, spring spawners also dominated the fishery of the 1940s. In Chaleur Bay, herring was the most economically important species after lobster and cod. A large percentage of older herring made up the catches in these areas and the view of Day (1957a) and Tibbo (1957) at the time was that fishing pressure could be increased.

The spring spawner TAC was exceeded from 1994 to 1996 and was nearly caught in 1997 and 1998 (Fig. 6). Most of the spring spawner inshore catches occur during the spring season in areas 16C and E (Table 2; Fig. 2).

The fall spawner TAC has not been exceeded since 1986 (Fig. 6). By agreement, within industry and not by regulation, fall inshore catches are for a roe market, and fall purse seine catches are for a filet market. Most of the fall spawner inshore catches come from 16B during the fall fishing season (Table 2; Fig. 6).

Table 2. Catch (tonnes) by season and area for inshore herring fisheries in the southern Gulf of St. Lawrence. Catches compiled using Zonal Interchange Files (ZIF) raw data files for 1986, and 1988-1998 spring. For 1987 spring and all fall years, purchase slip files were used.

SPRING SEASON

	Area							
Year	16A	16B	16C	16D	16E	16F	16G	Total
86	234	1439	2282	328	3731	66	266	8347
87	206	4089	3082	106	3841	134	38	11496
88	78	6616	3560	108	2041	158	122	12682
89	88	3827	1556	74	5080	134	62	10822
90	62	1715	2232	167	4285	141	17	8618
91	26	2139	5159	193	5018	127	16	12678
92	26	2856	4348	243	4699	146	54	12372
93	34	2377	4533	885	6893	200	124	15047
94	129	1550	6187	218	10499	154	71	18809
95	13	1029	4799	1039	6993	95	27	13995
96	123	460	5380	1628	8428	37	40	16096
97	23	274	3072	619	9221	18	2	13229
98	60	219	3023	1907	7541	176	607	13533
Mean 93-97	64	1138	4794	878	8407	101	53	15435

FALL SEASON

	Area							
Year	16A	16B	16C	16D	16E	16F	16G	Total
86	124	25959	93	0	1570	5816	6638	40199
87	208	31653	902	1	1090	9495	8660	52009
88	68	22111	1254	9	2591	9141	6102	41276
89	95	26431	1015	0	517	3160	2905	34123
90	110	31926	753	2	2405	10343	10957	56496
91	34	17181	1559	1	3242	1906	3122	27044
92	35	23559	1789	18	2540	1919	3160	33019
93	87	14597	3062	618	1977	935	1786	23062
94	74	34473	4086	1460	2118	8095	3483	53789
95	77	29448	5164	1901	4216	10113	3816	54735
96	86	21381	2817	1448	4688	7754	7608	45782
97	17	16540	2008	163	3969	6218	6132	35047
98	10	17845	1844	1213	5215	5466	7204	38797
Mean 93-97	67	23210	3468	1118	3347	6664	4514	42388

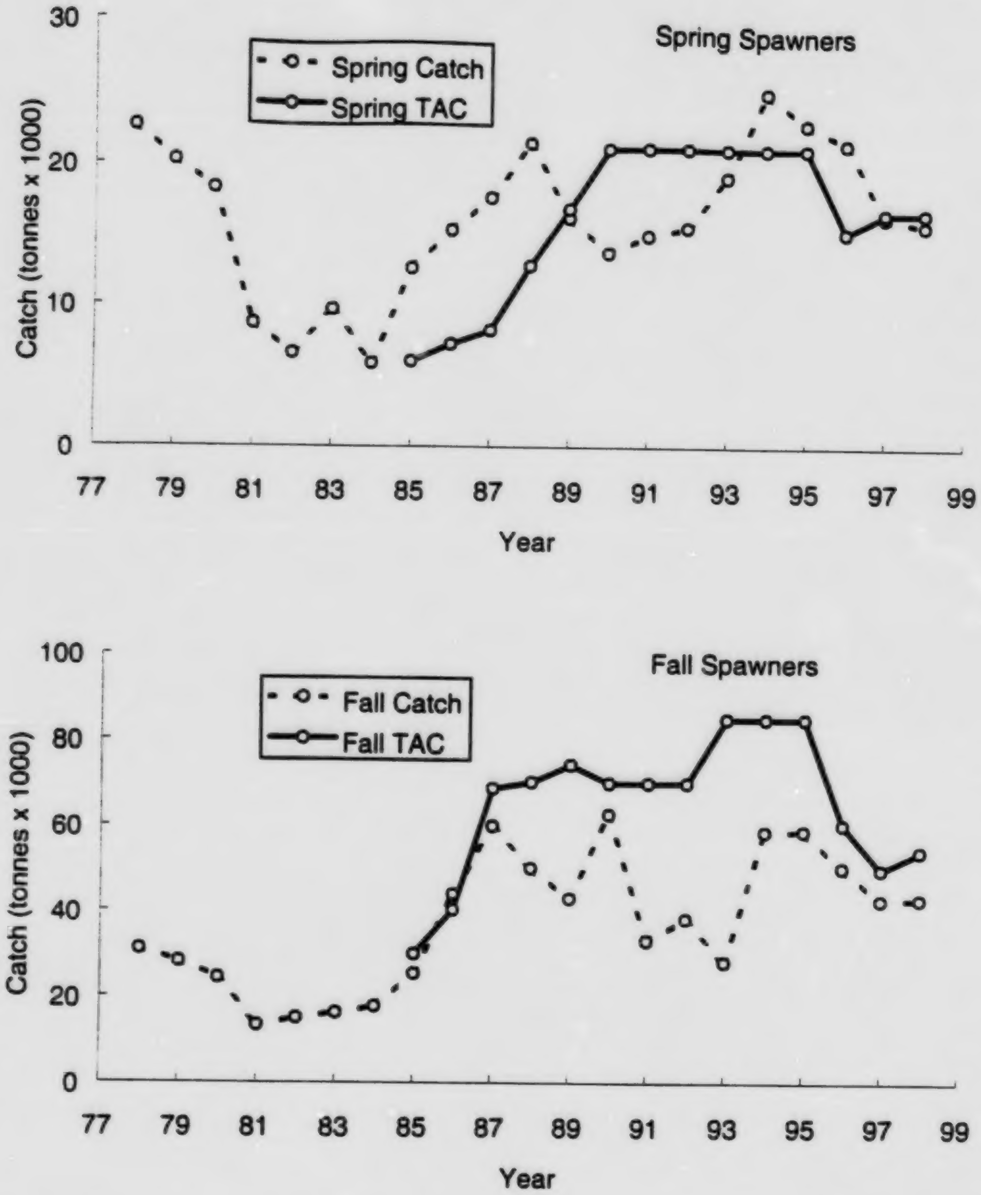


Fig. 6. Catch of spring and fall spawning herring in the southern Gulf of St. Lawrence by inshore gillnet and purse seine fleets compared to the TAC.

3.6 Influence of market on catches

Market conditions have played a large role in determining catch levels in this fishery. Prior to 1965, landings were primarily by fixed gear (Winters and Hodder 1975) and markets varied by area. Catches went to canned round, kipper snacks, and smoked bloaters in the Northumberland Strait, to smoked bloaters in the Magdalen Islands, and for bait in Prince Edward Island and Nova Scotia (Day 1957b). With the discovery, in 1965, of herring over-wintering areas in southern Newfoundland, catches increased considerably as a purse seine fleet expanded from 1 to 50 vessels by 1968 (Winters and Hodder 1975). The increase in purse seiners and catches was followed by an increase in reduction plants for the production of herring meal and oil (Winters and Hodder 1975). Food markets opened in Europe as a result of the declines in Northeast Atlantic stocks and by 1972, 40% of total landings were sent to European markets (Winters and Hodder 1975). In the early 1980s a Japanese roe market for fall spawners was developed and most of the fall inshore catch goes for this market at the present time. Currently, spring catches by both fleets remain primarily for smoked, filet, or bait markets.

The price for roe has a considerable effect on fall inshore catch and effort. The price has varied from $0.03/pound to $0.20/pound since 1983. A gillnetter requires about $0.06/pound to break even. In the early 1990s, when the price dropped to $0.03 cents, effort declined considerably. In the 1940s, the price for herring was about $0.01/pound. Prices for the food market currently vary from $0.07 to $0.09/pound. Spring prices for smoked and bait markets are subject to less fluctuation and usually vary between $0.15 to $0.20/pound (Day 1957a,b; Claytor and LeBlanc 1999).

3.7 Fishing methods

The fall and spring gillnet fisheries differ in the type of fishing and the size of nets. For example, most spring gillnets are either 2 1/4" to 2 1/2" and are 14 to 19 fathoms long. At one time, 2 5/8" was the most commonly used mesh size throughout the southern Gulf fall inshore fishery. Recently, in Escuminac, New Brunswick; Pictou, Nova Scotia; eastern Prince Edward Island; and western Prince Edward Island there have been an increasing number of individuals using 2 3/4" or 2 7/8" mesh. Nets used in the fall are similar in length to the spring, 14 to 18 fathoms long (Claytor and LeBlanc 1999).

Fishing methods differ between the two seasons. For example, in the spring almost all nets are anchored overnight and hauled the next morning. In the fall, spawning schools are searched for, and nets are set when a school of sufficient size is found. In Escuminac, New Brunswick; Chaleur Bay, Quebec; the Magdalen Islands, and the Acadian Peninsula, New Brunswick nets are fished with one end tied to the boat and the other end anchored. In other areas, nets are anchored at both ends and two or more strings may be set (Claytor and LeBlanc 1999). Purse seiners generally fish in depths of 20 to 40 metres. Seines are about 800 m long.

3.8 Fishing effort - Inshore

Since 1978, the number of nets has been estimated for the entire southern Gulf, without distinction for area. Since 1986, the number of nets has been estimated for areas which account for most of the landings. In the late 1970s and early 1980s, about twice as many nets were used in the fall fishery as in recent years (Table 3). These estimates indicate that until recently fewer nets were used in the Acadian Peninsula, New Brunswick than in other areas in the fall (Table 3). Recently, the number of nets used in other areas has declined and are now equal or only slightly above the numbers used in the Acadian Peninsula (Table 3).

Number of nets in the spring have been estimated by area since 1986 and indicate that for the two major fishing areas, fewer nets are used in Escuminac, New Brunswick than southeast New Brunswick, except for 1998 (Table 3).

3.9 Fishery - Industry views

Industry input for the assessment is acquired during workshops held in November and from a phone survey conducted from December to January. Workshops have been held each year beginning in 1994 and the phone survey began in 1986.

Table 3. Average number of nets used during the major fall and spring herring inshore fisheries in the southern Gulf of St. Lawrence.

Year	Fall Fisheries				Spring Fisheries	
	Pictou, Nova Scotia	Acadian Peninsula, New Brunswick	Western Prince Edward Island	Eastern Prince Edward Island	Escuminac, New Brunswick	Southeastern New Brunswick
86	10	7	10	10	25	28
87	10	5	8	8	21	40
88	9	7	10	10	19	33
89	6	6	8	11	20	31
90	7	6	10	7	20	35
91	10	5	12	7	16	37
92	9	6	7	9	15	30
93	5	6	7	9	18	31
94	6	7	7	12	15	31
95	7	6	8	8	22	34
96	6	5	8	8	18	29
97	5	5	7	7	19	27
98	6	6	8	8	26	26

Workshops are used to explain the assessment data for the coming year, resolve conflicts between assessment biologists and industry over resource trends, and plan for co-operative projects (Claytor 2000).

The phone survey collects information on the fishery and opinions on abundance trends. A subset of active commercial license holders, stratified by area, are phoned and asked a series of questions concerning number and size of nets used, frequency of fishing and how the abundance in the current year compares to the previous year and their views on long term trends. In 1998, 128 spring gillnetters and 167 fall gillnetters were surveyed out of a total of 2400 active licenses.

3.10 Assessment models

Formal assessments began with the International Commission for Northwest Atlantic Fisheries (ICNAF) in 1975 (Winters and Hodder 1975). These first assessments, including initial assessments conducted under the auspices of the Department of Fisheries and Oceans (DFO) (Winters et al. 1977; Winters and Moores 1978, 1979; Lett et al. 1978), used purse seine catch rates as the principal abundance index. Estimates of combined spring and fall spawner biomass were made using sequential population analysis models, as well as separate spring and fall estimates.

In the early 1980s, gillnet catch rates began to be used as the principal abundance index. Interviews and aerial surveys (Cleary 1981, 1982, 1983; Messieh 1984) gathered effort data. Trap catches on the Magdalen Islands were investigated as an index for that area but no formal assessment model, other than trends, were examined (Powles et al. 1979). Data inconsistencies and analytical problems plagued these assessments. Results often differed considerably between assessments depending on method and data treatments (Fig. 7). The situation in 1983 was summed up by one author of the assessments: "4T herring stock assessment is based on much imprecise data: real total catch is not known, various catch rate indices are biased, the spawning type and age assignment of fish is still often subjective, and recruitment is almost impossible to predict" (Cleary 1982).

Subsequent assessments improved on the estimates of effort using the phone survey and index gillnetters (for examples see Ahrens 1985; Clay and Chouinard 1986; Chadwick et al. 1989; Claytor and LeBlanc 1999). Poor spring inshore catch statistics precluded assessments of the spring stock using sequential population analysis until an improved dockside system came into effect in 1990.

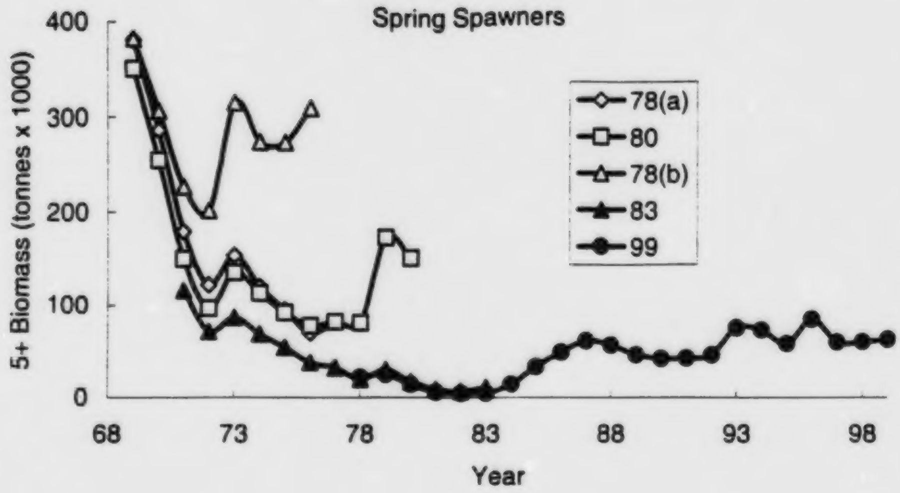
An ADAPT-VPA is currently the main assessment method. Separate assessments are provided for spring and fall spawners. Catch and weight-at-age matrices from 1978 to the present are estimated for each spawning group by fishing area. Gillnet catch rates (1978-present) are the main abundance indices used to calibrate the VPA. For the spring spawners, catch rates from the Escuminac, New Brunswick and southeast New Brunswick fisheries are used. For the fall spawners, catch rates from all areas are used but the time series is split into two time periods corresponding to the year in which there was a major shift in mesh size used in the gillnet fishery. The first time period is from 1978-1991 when the predominant mesh size (75% - 91%) was 2 5/8". The second time period is after 1992 when the percentage using 2 5/8" declined (54% - 67%) in favour of larger mesh sizes 2 3/4" - 2 7/8". Acoustic biomass estimates are used as a second index for spring spawners where there are correlations within cohorts over time, but not for fall spawners where correlations within cohorts are not significant.

3.11 Acoustic surveys

The first extensive acoustic surveys used small boats (< 50 feet) and were done from 1946 to 1949. No biomass estimates were made but herring were found during spring and fall surveys along the Gaspé coast and in Chaleur Bay. In addition, extensive schools of fish were found in the Northumberland Strait areas of New Brunswick, Nova Scotia, and Prince Edward Island and around the Magdalen Islands. Maps of these distributions look similar to those of today. The conclusion from these surveys was that large spring spawning concentrations in the southern Gulf of St. Lawrence might be purse seined successfully (Leim et al. 1957).

Beginning in the mid 1980s, an acoustic survey was designed to estimate biomass in order to develop an abundance index for spring and fall spawners in the southern Gulf of St. Lawrence (Cairns et al. 1989). Inconsistencies in survey techniques and high variance prohibited its use in assessments until 1999, when a consistent data series from 1994 to 1998 was developed and utilized in the assessment model (Claytor and LeBlanc 1999). This index includes Chaleur-Miscou (Fig. 8) strata surveyed consistently from 1994 to 1999, and includes only years when all transects were done at night and the same vessel, transducer, and sounder were used. Each year the survey has concentrated on Chaleur Bay but additional areas north of Prince Edward Island and Cape Breton are scheduled and are sometimes completed each year (Fig. 9). In each of these surveys, sampling to determine biological characteristics and to estimate target strength was carried out wherever major concentrations were observed. The acoustic survey catch-at-age was estimated using samples collected from each stratum. The catch-at-age for the survey was weighted by the signal strength in each stratum. The numbers-at-age, scaled to the catch rate index formed the age dis-aggregated abundance index from this survey.

In general, 50 to 100% of the fall spawners have been observed in the Chaleur-Miscou strata, including years when North PEI and Cape Breton, as well as, Chaleur-Miscou have been surveyed. In contrast, the percentage of spring spawners found in Chaleur-Miscou strata has varied from 80 to 100% in all years, including years when North PEI, and/or Cape Breton, as well as Chaleur-Miscou strata were surveyed.



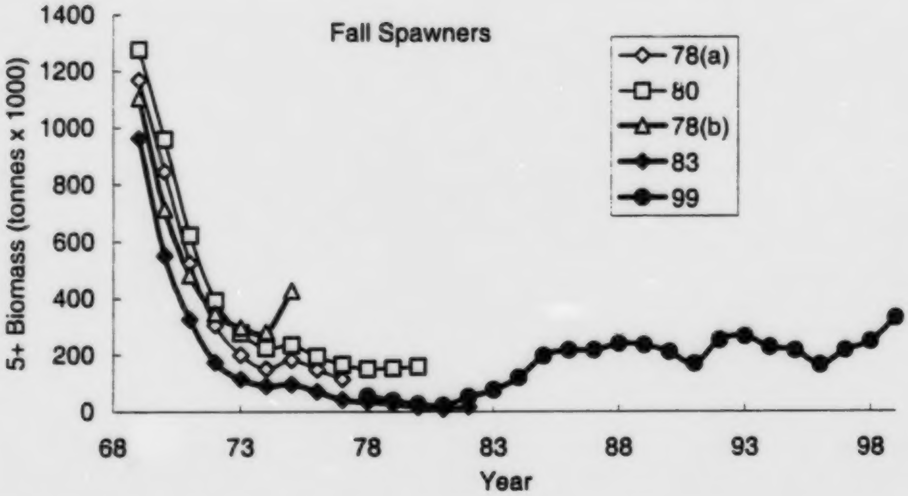


Fig. 7. Biomass estimates using sequential population analysis and ADAPT-VPA for selected southern Gulf of St. Lawrence herring assessments. Estimates differed among years depending on tuning index. Years prior to 1983 used purse seine catch rates as the tuning index, 1983 and 1999 used gillnet catch rates as the tuning index.

3.12 Trawl surveys

Surveys with mid-water and bottom trawls were also completed between 1946 and 1949. While these surveys caught herring, they were not very useful in providing information on stock status or distribution (Leim et al 1957). An annual bottom trawl survey throughout the southern Gulf of St. Lawrence has been conducted consistently during the month of September from 1971 to 1998. While this survey has not been used as an abundance index it does seem to follow year-classes and tracked contraction of the stock range during the years of depletion and the recovery in the mid 1980s (Claytor and LeBlanc 1999). During the 1990s herring have been found primarily along the north coast of Prince Edward Island and through the Northumberland Strait (Fig. 10).

3.13 Reference points

Since the first assessments the management goal for this stock has been to restrict fishing mortalities to below $F_{0.1}$ levels. Reference points have been calculated from yield per recruit models with $F_{0.1}$ varying from 0.30 to 0.44 per year whenever it has been calculated (Winters et al. 1977; Cleary 1981: Claytor et al. 1995). Doubleday (1985) modeled recruitment trends and errors in biomass estimates to investigate the effects of fishing at various levels on herring stock stability. He concluded that an average fishing mortality of 0.2 would allow about 75% of the theoretical maximum yield to be taken and would not dramatically reduce or de-stabilize stocks. If the exploitation rate exceeds 0.3, decline of spawning stock to less than one average recruiting year-class can be expected once every 10 years.

In 1997, a workshop was held that identified a number of ecological and life history target or reference points for herring in the southern Gulf of St. Lawrence, Bay of Fundy, Scotian Shelf, and Cape Breton. These included maintenance of all spawning components in time and space and healthy age structure (Anon 1997). To date these targets have not been quantified.

3.14 Population trends

The overwhelming feature of population trends in many herring stocks, including the southern Gulf of St. Lawrence, is one of large year-class fluctuations. These fluctuations were observed as early as the 1940s when Day (1957a,b) noted that the 1939, 1941, and 1943 year-classes were strong, but that the 1940 and 1942 year-classes were weak. Similarly, after the decline in population resulting the from an epizootic in the mid 1950s, the very large 1958 fall and 1959 spring year-classes supported the fishery for 10 years (Winters and Hodder 1975). Poor year-classes combined with high fishing levels led to the decline during the late 1960s and 1970s (Winters and Hodder 1975). Since 1978, above average year-classes continue to drive the fishery for periods of 4 to 5 years (Figs. 7, 11, 12).

Fluctuating year-classes tend to obscure stock recruitment relationships. Nevertheless, these relationships have been demonstrated for stocks with long time-series of data such as Norwegian spring spawners (Doubleday 1985, Hilborn and Walters 1992). Southern Gulf of St. Lawrence herring exhibits two stock recruitment modes for spring and fall spawners. The first mode consists of low stock sizes and produces only below average recruitment. The second mode consists of high stock sizes and produces a range of recruits from below average to very high. The collapse of many herring fisheries in conjunction with unexpectedly high fishing mortalities indicates that recruitment overfishing occurs in herring stocks (Patterson 1992). Managers of herring fisheries must consider that this is a probable outcome of high fishing rates.

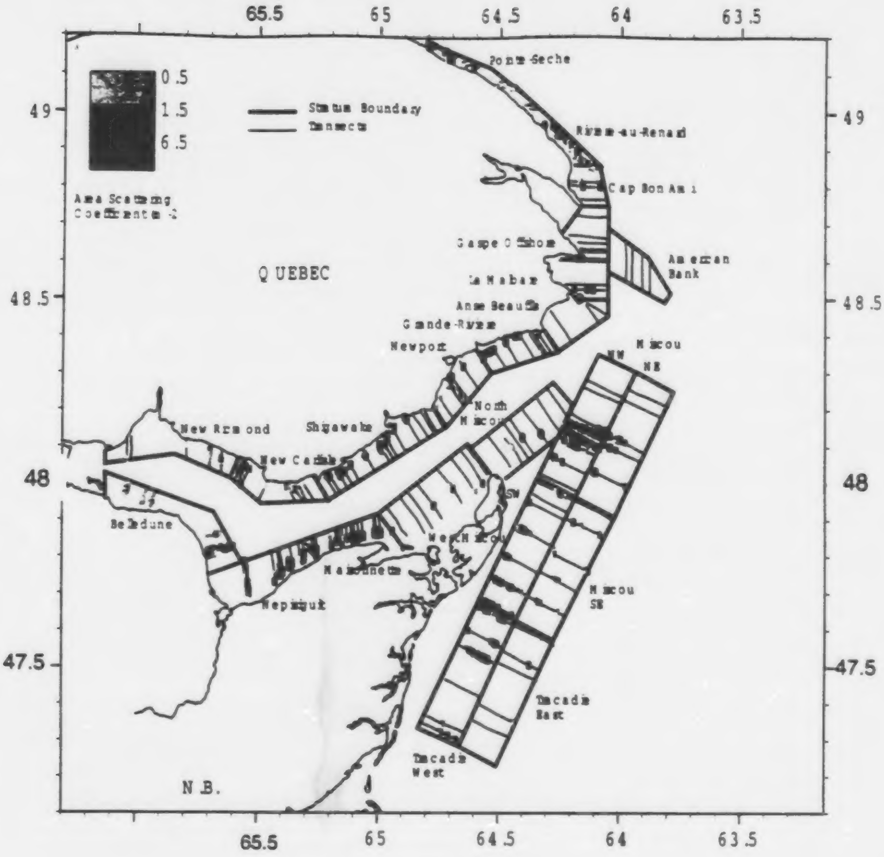

65.5
65
64.5
64
63.5
49
48.5
48
47.5
0.5
1.5
6.5
Area Scattering Coefficient
Stratum Boundary
Transects
QUEBEC
N.B.
Pointe-Seche
Rivière-au-Renard
Cap Bon Ami
Gaspe Offshore
American Bank
La Malbaie
Anse Beaufils
Grande-Rivière
Newport
Miscou
NW
NE
North Miscou
New Richmond
Shigawake
New Carlisle
Belledune
SW
West Miscou
Maisonnette
Nepisiguit
Miscou SE
Tracadie East
Tracadie West

Fig. 8. Chaleur-Miscou strata and acoustic transect locations for southern Gulf of St. Lawrence herring acoustic survey with relative backscatter, Sept. 21 to Oct. 2, 1997.

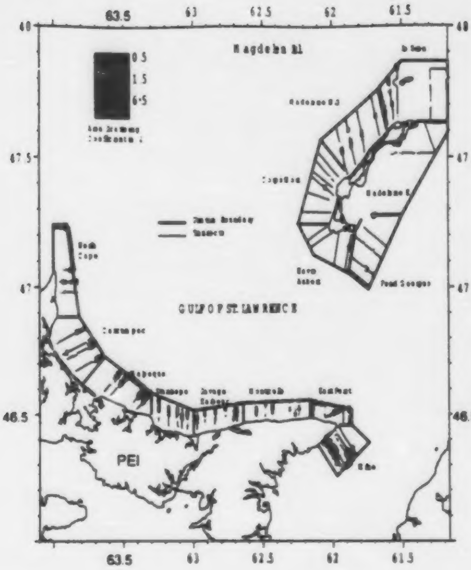
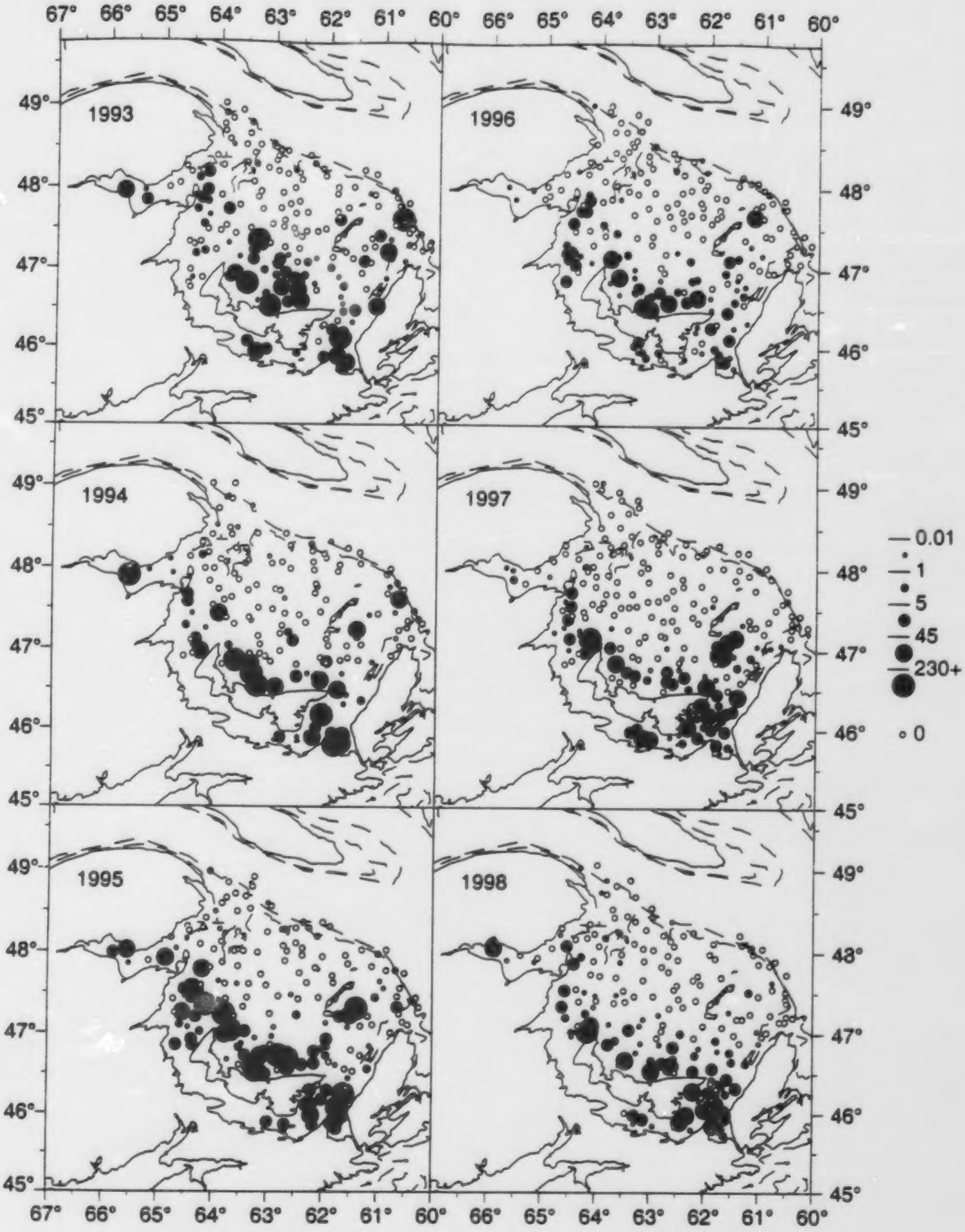

63.5
63
62.5
62
61.5
48
47.5
47
46.5
0.5
1.5
6.5
GULF OF ST. LAWRENCE
PEI

Fig. 9. Prince Edward Island and Magdalen Island strata and acoustic transect locations for southern Gulf of St. Lawrence herring acoustic survey, Oct. 2 to Oct. 5, 1997.



67°
66°
65°
64°
63°
62°
61°
60°
49°
48°
47°
46°
45°
1993
1996
1994
1997
1995
1998
0.01
1
5
45
230+
0

Fig. 10. Herring (kg/tow) in September bottom trawl survey in the southern Gulf of St. Lawrence 1993-1998.

Advice on fishing levels, with respect to estimated or inferred trends in biomass began in 1957. At that time, the lack of appreciable change in size and age composition of the stocks of herring since 1914 led to the conclusion that the commercial fishery had not reduced the level of abundance. In addition, accumulations of large, old fish in the spring and fall suggested that southern Gulf of St. Lawrence herring populations were underfished (Day 1957a,b). A great deal of effort was spent looking for ways to increase the yield from these stocks.

Efforts to increase yield were largely successful. The 1975 assessment estimated a decline in combined spring and fall spawners from 1,840,000 tonnes in 1965 to 506,000 tonnes in 1971 for total biomass. Adult biomass in 1971 was 12% of the 1965 value. The very large 1958 fall and 1959 spring year-classes, which appeared after the devastating epizootic of the mid-1950s were the principal reason for the high biomass in the mid-1960s. These assessments concluded that excessive fishing mortalities accelerated a decline which would have occurred anyway because the strength of the 1958 and 1959 year-classes was so atypical. Fishing mortalities were estimated to be below 0.4 for these years.

Subsequent estimates of biomass changed appreciably as stock assessment methods and data were updated. In general the trend was that successive assessments estimated higher fishing mortalities and lower population sizes than previous assessments (Fig. 7).

Current stock levels estimated from the VPA for fall spawners are among the highest observed since 1978. Uncertainties resulting from difficulties in estimating incoming recruitment and low abundance indices in the acoustic survey moderate this view (Fig. 11). Current stock levels estimated from the VPA for spring spawners indicate a stock size that is about average since 1985 but above the low levels observed in the late 1970's and early 1980's (Fig. 12). Estimates of 4+ spring spawner biomass peaked in 1995, when the 1991 year-class, the largest since 1978, entered the fishery. This year-class has been supporting the fishery since it first appeared in 1995. The 1992 year-class was among the lowest since 1978, but the two most recently estimated year-classes, 1993 and 1994, have been above average. The result of these trends in year-class strength is that the biomass levels have been relatively stable for the past four years. The $F_{0.1}$ fishing levels were between 16,000 tonnes and 18,500 tonnes from 1996 - 1999.

Prior to 1998, estimates of 4+ fall spawner biomass peaked in 1991, when the very large 1987 year-class appeared in the fishery. The population declined until 1996, when the large 1992 year-class appeared in the fishery. Since then, year-classes have been above average and the population is growing. The $F_{0.1}$ fishing levels were between 50,000 tonnes and 60,000 tonnes from 1996 -1999.

Current assessment advice is provided for each seasonal spawning stock as a whole. The division of the total TAC amongst the components may be a way of reducing the chance for the kind of overall stock collapse that has been seen in the past. It does not, however, guarantee that individual components will not be lost, as emphasized by the dramatic decline in spring catches in Chaleur Bay since the 1940s. In 1995, several local indicators identified that a decline in the fall Chaleur Bay stock had occurred. These negative indicators led to slight adjustments in area allocations but they have not been maintained and the danger of a repeat or unnoticed decline is present under the current system. One way to reduce the vulnerability of herring stocks to overfishing is to consider the fishing effects on individual stock components. In the past, this information has been difficult to obtain and there was no model for objectively assessing these impacts. The method investigated in this thesis may provide such a system. An evaluation of the scale of stock structure in the southern Gulf of St. Lawrence will be used to define a model for area assessment and management of these herring stocks.

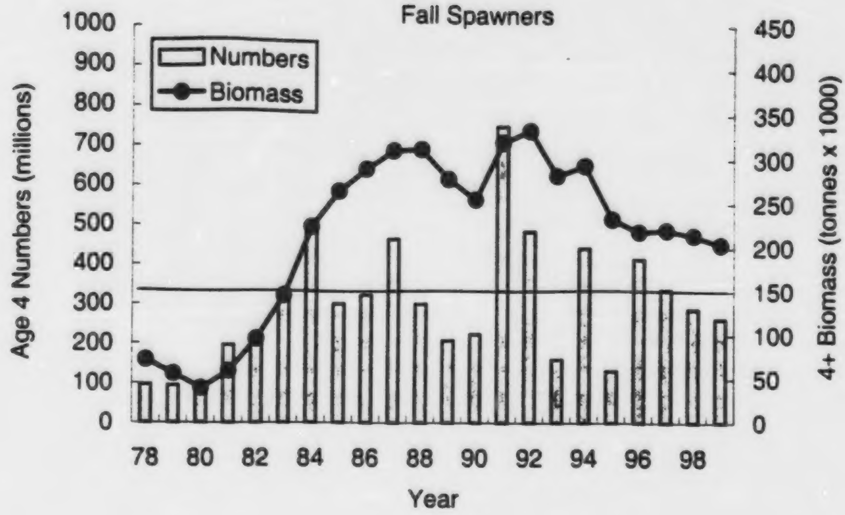


Fig. 11. Age 4 numbers-at-age, 4+ biomass, and average recruitment of age 4 (horizontal line) for southern Gulf of St. Lawrence herring fall spawners estimated from ADAPT-VPA.

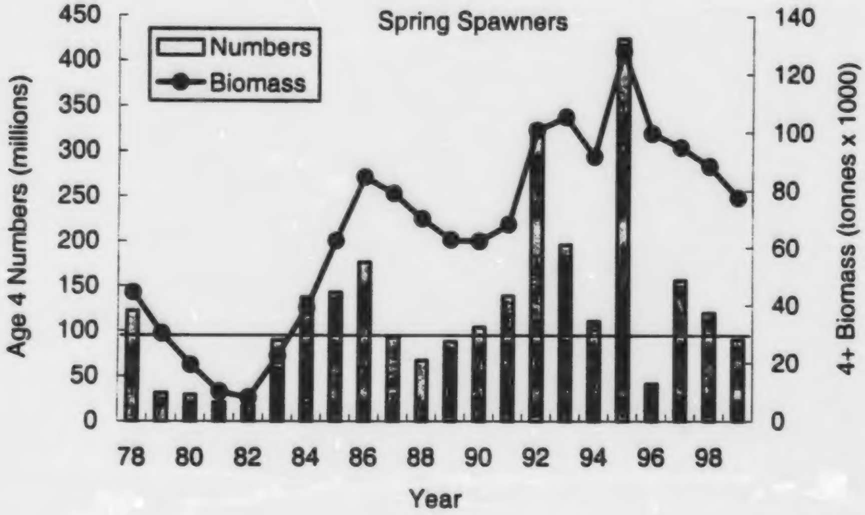


Fig. 12. Age 4 numbers-at-age, 4+ biomass, and average recruitment of age 4 (horizontal line) for southern Gulf of St. Lawrence herring spring spawners estimated from ADAPT-VPA.

4. Area assessments

4.1 Background

Even before the publication of 'Origin of the Species' (Darwin 1859) fisheries biologists were embroiled in a bitter debate over the population organization and management of Atlantic herring. In 1832 Nilsson, a zoologist hired by the Swedish government to investigate the 1808 collapse of the Bohuslan fishery, concluded that herring existed as discrete local populations and that the collapse of the fishery was due to local overfishing. He asserted that local control and regulatory powers would constitute the best management of herring fisheries. In 1854, Cleghorn joined the debate by reporting that herring existed in discrete populations and that fluctuations in landings were the result of overfishing local populations and not changes in migration routes (Sinclair and Solemdal 1988).

This conclusion and recommendation were in sharp contrast to the alternative view held at the time, which was that herring existed as one panmictic population that migrated between polar northern areas and European coastal waters (Sinclair and Solemdal 1988). Dodd and Anderson in Europe, and Gilpin in North America, during the mid-1800s, were the principal supporters of this hypothesis. The management implications of this alternative view were that changes in abundance, such as those observed in the Bohuslan fishery, were the result of changes in migration routes and not from local overfishing.

The arguments for the discrete population hypothesis were not widely accepted at the time. The differences in spawning times, size composition, morphology, and quality of herring spawning in different areas identified by Nilsson and Cleghorn were subject to considerable criticism. Heincke's, 1878-1898, work on the population structure of herring supported the discrete population hypothesis and made population structure the focus of research questions at the beginning of the 20th century. Ironically, Heincke demonstrated that Nilsson was wrong about the origins of the herring in the Bohuslan fishery. He found that these fish originated from a spawning stock in the Jutland area of the North Sea and that they overwintered in the area of the Bohuslan fishery. Subsequently, Ekman and Petterson found that the regular disappearances of herring in the Bohuslan fishery resulted from shifts in water mass characteristics related to tidal cycles (Sinclair and Solemdal 1988).

4.2 Stock structure evidence

In spite of a century of investigations, the divergence regarding the population organization of herring and the consequences of management alternatives remains. Genetic evidence appears to be consistent with a panmictic hypothesis, but this consistency cannot refute the discrete population hypothesis. Those approaching the problem from a genetic perspective suggest two management approaches. One is continuing to manage populations as if they were separate until the management consequences of greater variation within, rather than between populations is determined. Another management approach suggested is to incorporate the lack of genetic differentiation among herring populations into management plans. However, those suggesting this incorporation do not suggest how this could be done (Smith and Jamieson 1986; Smith et al. 1990). Alternatively, ecological evidence is consistent with a highly structured population organization. Those approaching management from this point of view support the continued collection of data and preservation of individual spawning components.

4.3 Ecological perspective

Schmidt and Hjort continued the work of Heincke at the beginning of the 20th century. Their results were consistent with the hypothesis that herring exist as population units that are to some degree distinct and isolated from other units. They hypothesized that the degree of isolation between units made them vulnerable to depletion by overfishing (Sinclair and Solemdal 1988). The collapse of Atlanto-Scandian, North Sea, Georges Bank, and Magdalen Island stocks and fisheries during the 1960s and 1970s is consistent with this vulnerability hypothesis (Saetersdal 1980). In addition, the stock structure of southern Gulf of St. Lawrence herring changed from one of predominately spring spawners in the population and fisheries (Day 1957a,b; Winters and Hodder 1975) to one of predominately fall spawners after the near collapse of the population from the fungal epizootic in the mid-1950s. After the epizootic a very large fall spawner year-class (1958) and spring spawner year-class (1959) occurred, but because the fall spawner year-class was so much larger it shifted the structure of the population (Moores 1980). Southern Gulf of St. Lawrence herring are predominately fall spawners today (Claytor and LeBlanc 1999). The decline of the southern Gulf of St. Lawrence herring stock in the late 1960s and early 1970s had the additional effect of changing the predominant overwintering area of the stock, from southern Newfoundland to Cape Breton. Herring were always present in the overwintering area of Cape Breton and it is likely that the purse seine fishery during the 1960s and 1970s preferentially harvested those migrating to southern Newfoundland. As a result, rather than the migration changing as some have suggested (Winters and Hodder 1975), it may be that the portion of the stock overwintering in Newfoundland was depleted. Herring have not been observed in southern Newfoundland during the 1990s (Claytor 2000).

Recent ecological studies have found that meristics and morphometrics can delineate and identify Atlantic herring spawning stocks. For example, width of scale annuli has been used to separate northern and southern Norwegian populations with 90% accuracy (Baroos and Holst 1995). Messieh (1972) and Messieh et al. (1989) used otolith nucleus width and several other otolith measurements to identify spring and fall spawning components in the southern Gulf of St. Lawrence.

In Atlantic Canada, Parsons (1973) identified three distinct groups of herring based on their meristic characteristics: one from the Magdalen Islands and southwestern Newfoundland, a second from southeastern Newfoundland, and a third from eastern Newfoundland. He found fewer meristic differences among fall spawners compared to spring spawners but the geographic affinities were similar. These geographic trends were consistent with those determined from the distribution of *Anisakis, a* larval nematode, in herring. In contrast, he found that morphometric characters were less useful and were not consistent with distributions expected from tagging results (Parsons 1975).

Tagging studies in eastern Newfoundland indicated that homing to spawning areas ranged from 65% to 95% with an average of about 81% (Wheeler and Winters 1984). In contrast, Atlantic salmon homing to natal river systems based on tagged returns was greater than 98% in a study by Stasko et al. (1973). When homing to the natal tributary within a river system was considered, the percentage homing was about 80% (Stasko et al. 1973). In contrast, cod that were tagged and transplanted to new areas behaved and migrated in the same way as the local stock into which they were transplanted (Otterlind 1985).

On a smaller scale, Jean (1967) using vertebral counts, head measurements, and growth rates, found differences in spawning herring sampled in the Gulf of St. Lawrence. The distinct areas were in the estuary of the St. Lawrence River, Ile Verte; Riviére Madeleine, Gaspé; and Anse-au-Gascon from the Québec side of Chaleur Bay.

Similar results have been found for European herring populations. Zulstra (1959) found evidence of three discrete groups of North Sea autumn spawning herring. Alternatively, Hulme (1995) reviewed 20 years of data and found that environmental influences had changed spawning times of North Sea herring groups and that vertebral counts of these groups were correlated with sea temperatures. He concluded that environmental influences on these characteristics were too strong to use them for stock delineation. In contrast, Chadwick and Claytor (1989) examined run-timing and fisheries timing in the southern Gulf of St. Lawrence for pelagic and anadromous species and found that they were consistent over years and areas. These consistencies occurred in spite of sea temperature changes over these years and areas. Similarly, Bradford and Stephenson (1992) found that egg weight varied among Atlantic Canadian herring populations and that mean population egg weights were not correlated with temperature at spawning time or temperature during the last two months of egg development. They also found spring spawners had lower fecundity than fall spawners.

A review of the biological characteristics of southern Gulf of St. Lawrence fall spawners indicated that dominant year-classes tended to occur in all six major spawning areas simultaneously (Fig. 13). Weights-at-age of the dominant ages in the inshore fishery were similar amongst northern, middle, and southern areas of the southern Gulf of St. Lawrence (Fig. 14).

Trends in changes in weights-at-age were similar amongst these areas as well. The Magdalen Islands, however, had quite a different age structure during its rebuilding phase, indicative of low exploitation rates relative to the rest of the southern Gulf in that area.

Fall spawning herring in the southern Gulf of St. Lawrence differed in trends of abundance indices and catch-timing. Catch rate correlations were significant only between Chaleur Bay and Escuminac, Escuminac and West Prince Edward Island, and Fisherman's Bank and Gulf Nova Scotia ($p<0.10$). These relationships are those that would be expected based on geographic affinities (Fig. 15) (Claytor et al. 1998b).

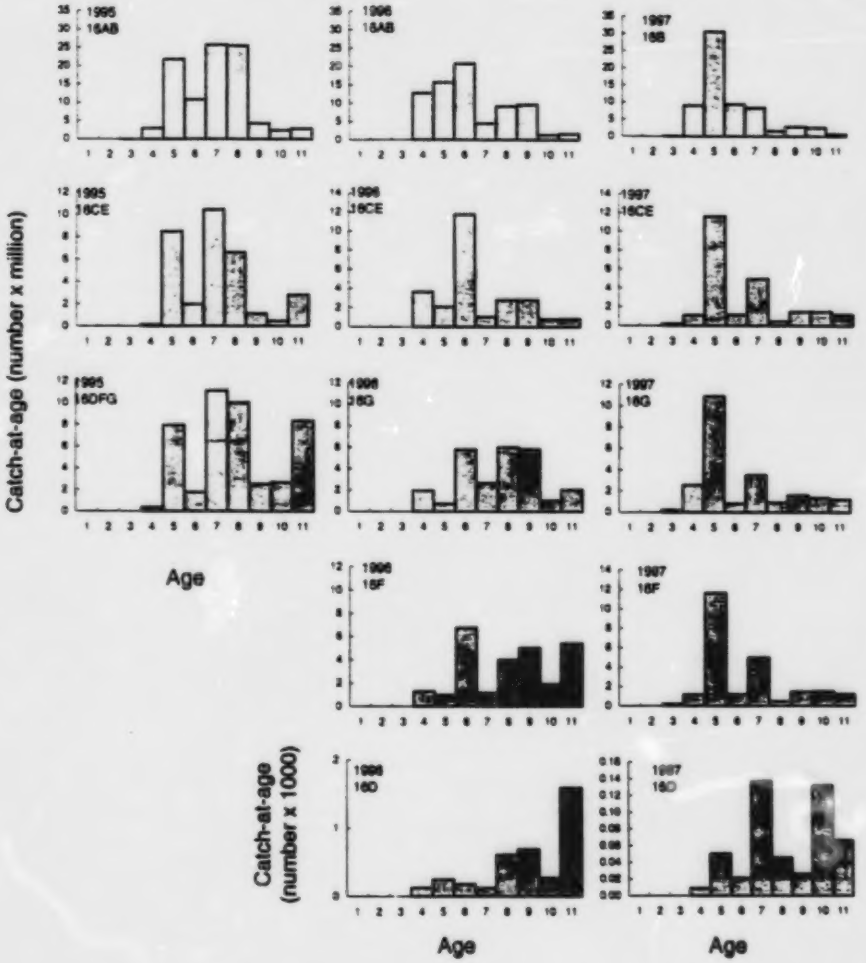
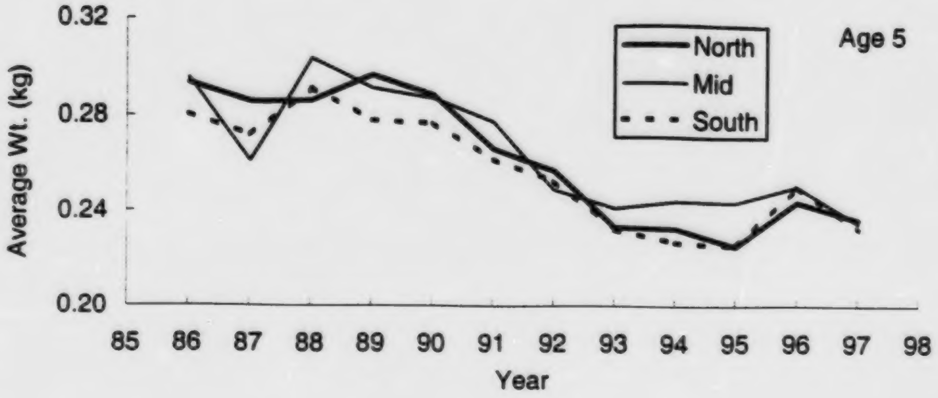


Fig. 13. Catch-at-age (numbers) for fall inshore herring fisheries in the southern Gulf of St. Lawrence from 1995 to 1997. Management areas (ex. 16D) are those indicated in Fig. 2. Numbers are in millions except for 16D where numbers are in thousands.



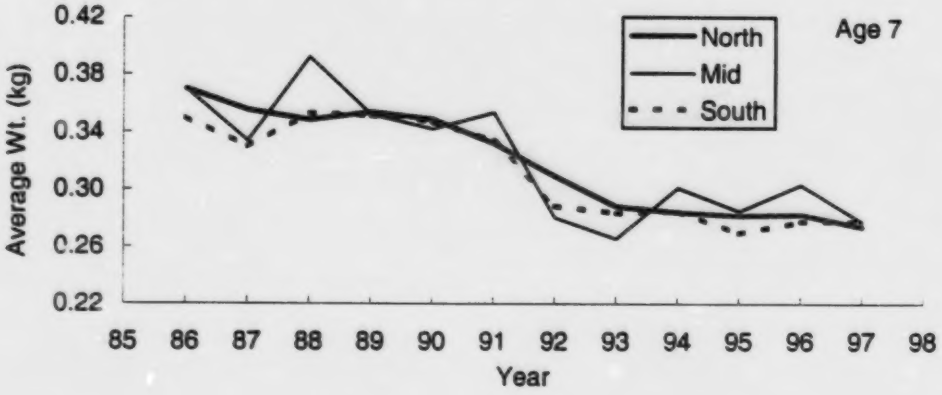


Fig. 14. Average weights-at-age for fall spawners by major areas in the southern Gulf of St. Lawrence inshore fishery. North includes NAFO Divisions 4Tmno, Mid includes NAFO Divisions 4Tfghjk, South is NAFO Divison 4Tl, Fig. 2.

Significant correlations for catch-timing only occurred between Escuminac and Pictou, Nova Scotia. These sites have little geographic connection and there is no obvious explanation for a correlation based on stock relatedness. Chaleur, Escuminac, and West Prince Edward Island have a similar catch timing, compared to Fisherman's Bank which is earliest, and Gulf Nova Scotia which is latest (Fig. 16) (Claytor et al. 1998b).

Each of the authors examining phenotypic characteristics such as meristics, morphometrics, or features such as growth rates recognized the difficulty of separating environmental and genetic effects in these analyses. Thus, from many of these studies it is not possible to assign a genetic parameter to the integrity of the spawning component. In addition, the tagging results and the overlap of phenotypic traits among populations is indicative of gene flow amongst neighboring Atlantic herring populations. Nevertheless, the slow recovery of depleted stocks, the change in population life history characteristics including spawning season and migration routes when stocks are depleted, the consistency of spawning time, and homing estimates are indicative of a species with a population richness that is closer to Atlantic salmon than Atlantic cod (Sinclair 1988). This definition is important because salmon are a species where large agreement on the need for individual population components in management plans has been established. Thus, life history investigations indicate that incorporating population factors into herring management plans that may be expected to improve the long-term performance of herring fisheries.

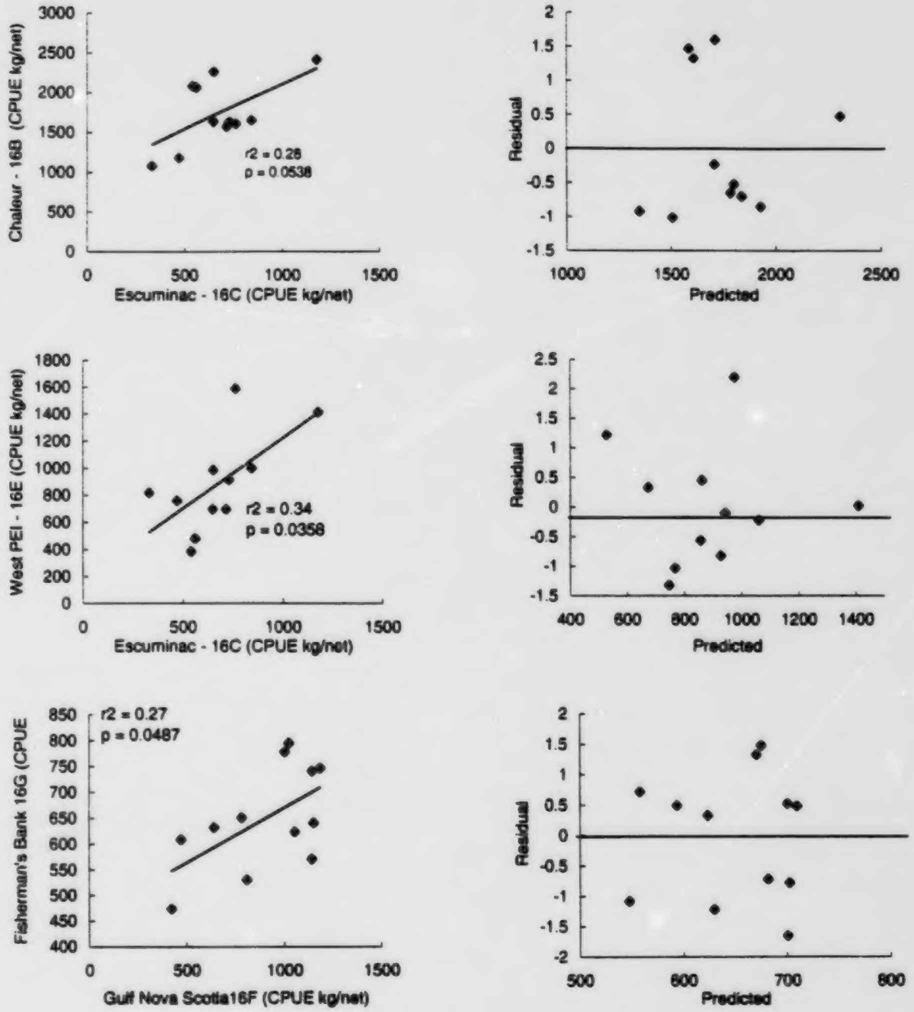


Fig. 15. Catch rate (kg/net) correlations between geographically adjacent fall herring inshore fishing areas in the southern Gulf of St. Lawrence. Management areas are shown in Fig. 2.

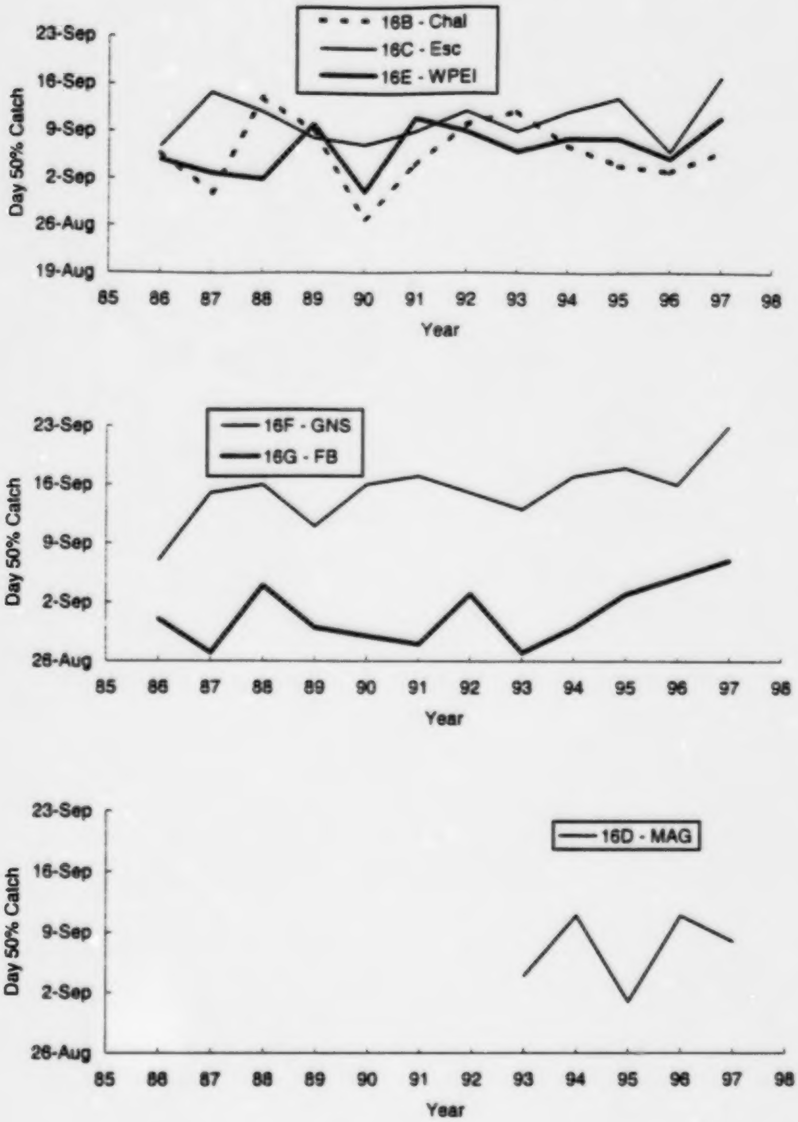


Fig. 16. Date when 50% of the herring were caught during the fall season in the southern Gulf of St. Lawrence inshore fishing areas, 1986 to 1997. Management areas are shown in Fig. 2. Abbreviations for areas are: Chal, Chaleur; WPEI, West Prince Edward Island; Esc, Escuminac; GNS, Gulf Nova Scotia; FB, Fisherman's Bank; MAG, Magdalen Islands.

Genetic studies based on protein and mtDNA patterns are remarkably consistent in their inability to differentiate spawning groups of Atlantic herring. These studies had a promising start with Ridgway et al. (1970) finding differences in esterase patterns between western Maine, USA and Georges Bank herring. Subsequent work beginning with Kornfield et al. (1982), Safford and Booke (1992), Ryman et al. (1984), Grant (1984), and King et al. (1987) on enzyme variability using electrophoretic techniques found that 99% of the variation was within populations even though they analzyed different but sometimes overlapping groups of fish. In contrast, only 82% of the variability of Pacific herring is within populations (Grant 1984). Kornfield et al. (1982) found differences between spring and fall spawners but the magnitude was small and the results were temporally unstable. Each of these studies concluded that it was not possible to identify the origin of individual fish using these genetic characteristics and that the average genetic distance among herring spawning groups was less than in other fish species.

Each of these research groups observed that there was a high probability of interchange between neighbors probably in larval mixing areas and at the adult stage in overwintering areas. However, they also note that at the observed Wright fixation index levels, that between 60 and 100 individuals exchanging between spawning groups would be required to maintain the levels observed.

Wright's index is defined as:

$$F_{st} = \frac{1}{4Nm+1} \tag{7}$$

where N is subpopulation size and m is the proportion of fish migrating and exchanging genes into each subpopulation over each generation.

It was also noted that while this could explain differences between neighboring groups, it does not explain the consistency between Baltic and west coast British Isle groups. Herring populations are of a size that genetic drift would not be apparent for a long time, especially if selection pressures were weak. Thus, drift would be slow and considerably longer than the 18,000 years since the last glaciation (Grant 1984; Ryman et al. 1984). This difficulty led Grant (1984) to propose a radiation model, in which a single population on one side of the Atlantic spread or radiated into several populations that do not now exchange. Similar arguments have been made for the high variability within, rather than between, pink salmon populations in western Canada and the United States. While there were major differences between even and odd year salmon spawners, there was little difference among rivers within these year-class groups. Aspinwall (1974) hypothesized that this lack of divergence among year-class groups was the result of the small number of genetic migrants and the short amount of time for differentiation since the last glaciation. Subsequent work has emphasized the importance of the small number of genetic migrants in homogenizing differences among otherwise separated populations (Adkison 1995).

Some research has found heterogeneity in genetic structure of herring populations. Stephenson and Kornfield (1990) used iso-enzyme differences, in conjunction with year-class patterns and homing estimates from other populations, to argue for the resurgence rather than re-colonization of Georges Bank herring. Jørstad et al. (1991) and Jørstad et al. (1994) using electrophoretic techniques in Norwegian populations found distinct genetic characteristics among fjord populations and that these populations were most similar to Pacific herring. They found enough heterogeneity among coastal and oceanic spawning components to indicate that herring in Norway were not one panmictic population and concluded that post-glacial radiation was consistent with their results.

The development of mtDNA procedures led to high expectations for the detection of genetic differentiation among herring populations. Kornfield and Bogdanowicz (1987) examined restrictive enzyme mtDNA patterns from three geographically disparate herring populations from Jeffreys Ledge, western Maine, southwest Nova Scotia, and Escuminac, New Brunswick for the southern Gulf of St. Lawrence. Although they found a number of unique composites they were not distributed in a manner that supported genetic differentiation. For example, Jeffrey's Ledge, Maine, contained the precursor for an Escuminac, New Brunswick composite even though these were the most geographically separated groups. As others before them, Kornfield and Bogdanowicz (1987), pointed out that small amounts of gene flow between groups would be enough to homogenize the differences among groups and that herring divergence would be slow to develop because of large population sizes. They concluded that their design was not sufficient to confirm the occurrence of current gene exchange between herring populations. They concluded as did Kornfield et al. (1982), Safford and Booke (1992), Ryman et al. (1984), Grant

(1984), and King et al. (1987) that resources like herring should be managed under the assumption that every spawning group is a semi-discrete entity.

Smith et al. (1990) and Smith and Jamieson (1986) had a different management perspective after reviewing these results. They concluded, as had the others, that the genetic evidence did not support isolated populations but was consistent with gene flow between populations. They concluded that there was no genetic justification for allocating separate quotas to spawning populations in the central and southern North Sea. They did, however, note that when fishing pressures were relaxed, stocks appeared to expand and when fishing pressure was increased they appeared to contract. Nevertheless, these studies indicated that gene flow among the populations was sufficient to maintain the genetic identity of the species. They termed this maintenance of genetic identity, in spite of contraction and expansion in response to fishing, a 'dynamic balance'. This 'dynamic balance' requires careful biological monitoring to determine the changing effects that environment and fishing activities have on the species. They recommend that management needs to take into account the high genetic variability within areas and low genetic differentiation between areas, but they do not specify a structure for taking these ideas into account.

Discordant results between phenotypic and electrophoretic characteristics have been observed even in species which have been found to be genetically isolated. Claytor and Verspoor (1991) found discordant patterns between each of the meristic, morphometric, and electrophoretic patterns between sympatric populations of resident and anadromous Atlantic salmon in a small Newfoundland lake. They hypothesized that phenotypic and electrophoretic variation is likely to be congruent only by coincidence, and that these characters likely evolve independently and are affected differentially by environmental effects. As a result, it becomes very difficult to separate vicariant or historical effects from present day ecological factors (Endler 1973; Endler 1982; Claytor et al. 1991). Where ecological and historical factors coincide we are not likely to be able to make any inference on relative causes for differences and similarities (Claytor and MacCrimmon 1988). These relationships are likely to be very difficult to sort out with herring using phenotypic and genetic characteristics. As Blaxter (1958) pointed out, it seems that herring exist as separate populations but how they originate, why they remain distinct, and how they are related remain unanswered. Another model for herring management must be sought.

4.4 Metapopulation model

The problem for herring management is that overfishing of local resources depletes these resources to low biological and economic levels for a considerable time. This effect occurs in spite of gene flow between neighboring populations. These effects contradict the development of fisheries management as one of fish stock management in which Paulik et al. (1967) identified the need for the preservation of a broad level of reproduction to enable a population to respond to environmental change, and emphasized the importance of preserving unique genes. Ricker (1972) defined a fish stock as "... fish spawning in a particular lake or stream (or portion of it) at a particular season, in which fish to a substantial degree do not interbreed with any group spawning in a different place or in the same place at a different season". A number of definitions of fish stocks were proposed during a major symposium on the stock concept in the early 1980s. Spangler et al. (1981) summarized these stock definitions as ..." local populations that maintain their recognizable genetic differentiation by separation of their spawning place or time". It is clear that none of these definitions resolve the management question for Atlantic herring, although MacLean and Evans (1981) came close by asserting that behavioural as well as genetic aspects of a population were important in defining stocks and maintaining populations.

The metapopulation model as defined by Cooper and Mangel (1999) is consistent with the above studies on herring population structure. In their definition, the spawning component is a deme or population, where a population is described as a group of con-specific individuals that are partially but not completely reproductively isolated. Dispersal between and among these populations links their abundance (weakly) and genetics (strongly) on short-term ecological scales, so that differentiation in population trends (e.g. due to differential harvest rates) can occur despite lack of genetic differentiation. These groups constitute linked populations that are referred to as metapopulations. They recommend that the populations within such metapopulations form the basis for management units. The final level in the metapopulation model is the evolutionary significant unit which contain one or more groups of metapopulations. It seems clear that herring exist as sets of linked metapopulations (McQuinn 1997), though as Blaxter (1958) indicated, the mechanisms that define and maintain these links are far from certain or agreed upon (Sinclair and Iles 1988; Smith and Jamieson 1986). Though, the generalization of "natal homing" as described by Cury (1994) must certainly play a role in creating local populations that are vulnerable to over-harvesting.

Cooper and Mangel (1999) provide a model for identifying and directing the type of data that should be collected for the management of metapopulations. In addition, their model provides a framework for assessing the appropriate management actions in this population structure. They first make a distinction between management to prevent extinction and management to maintain viable populations. Management to prevent extinction requires information on the immigration and emigration rates among the populations and on their reproductive rates. Management to maintain viable fisheries requires additional knowledge on the population trends in each component.

These requirements become particularly important if the metapopulation structure is sink-source, where populations with positive reproductive rate seed and maintain those with negative reproductive rates. If the whole metapopulation structure is not considered then management may concentrate efforts on improving conditions in a sink population, when the problem resides with the source population (Cooper and Mangel 1999). They also caution that an index on part of the system is not sufficient because it could represent the source or the sink and therefore bias conclusions regarding appropriate actions.

4.5 Management objectives

The management objectives for southern Gulf of St. Lawrence herring are clearly more than to prevent extinction. It is also a fundamental aim to sustain production at the relatively small spatial scales where various fishing communities see their future opportunities, i.e. the spawning group or local population scale. The combination of fixed exploitation rate strategies and ecological targets indicate that the management objective is to maintain viable populations (see above and Anon 1997), and this objective must be implemented at the local population scale given that local divergence in abundance (e.g. local overfishing) is a risk. As a result, determining population trends within each metapopulation is required. The data collection model investigated in this thesis is directed toward estimating abundance trends in these metapopulations. The lack of a robust estimator of these trends is the single most important piece of information preventing a change in the management plan of this stock from one of a global TAC, partitioned among groups without regard for local population trends, to one in which local population trends and biomass levels direct local fishing levels. The combination of the metapopulation model and the acoustic data collection investigated will provide a basis for the development of decision rules for the equitable distribution of fishing mortality among the southern Gulf of St. Lawrence spawning components. Development of this method and subsequent decision rules focuses attention on the information required to move the management of this species beyond the current empass resulting from uncertainty of abundance trends within and among southern Gulf of St. Lawrence metapopulations.

Previous methods to obtain these abundance trends used spawning bed surveys and side-scan sonar. Spawning bed surveys (Pottle et al. 1981; Messieh et al. 1985; Messieh and Pottle 1986; Cairns et al. 1993) provided egg mass estimates but were difficult to maintain because of high costs and labour requirements and their inability to identify year-class strength (Claytor et al. 1998b). Side-scan sonar techniques are useful auxiliary sources of information because data collection can continue during fishery closures and bad weather. However, their short range in shallow water makes them impractical as a primary source of abundance data in the southern Gulf of St. Lawrence (Trevorrow and Claytor 1998).

Collecting acoustic data during regular fishing activity has the advantage of being cost-effective and providing the fishing industry with the capability to collect data on problems of interest to them during regular fishing activity or auxiliary surveys. The following two chapters present first, the results of the analysis of the acoustic data collected during regular fishing activity by the inshore gillnet and mid-shore purse seine fleets, and second, the results of a simulation model used to test the analytical method. The analysis of the acoustic data is presented first because the simulation model is based on the simulated data collected and analyzed from the inshore gillnet fishery. The final chapter discusses how these data could be used to manage the southern Gulf of St. Lawrence herring fishery.

5. Distributing fishing mortality in time and space

5.1 Acoustic data collection and preparation

Fishing vessels, during regular fishing trips and surveys, collected acoustic data. However, only data collected during regular fishing trips were examined in this thesis. Fishing captains acoustically map fish abundance in their area while searching for fish and these data were used to estimate abundance of herring for each individual fishing night. The principal assumption tested by collecting these data is that the relative estimates of abundance were proportional over the range of possible boat searching patterns, fish aggregation and movement patterns, and stock sizes, and hence can be defined as relative abundance indices. Catches in the fishing areas were divided by relative abundance indices to estimate relative fishing mortalities or exploitation rate indices. These could then be used to advise managers on ways to distribute fishing mortality equitably amongst all parts of the spawning component.

These data also allow assumptions associated with traditional catch rate analysis, such as proportionality, to be examined relative to the acoustic indices. In addition, the development of fishery abundance indices that are not currently available can be tested. For example, with these data, it is possible to identify search distance and time, and handling or fishing time, two characteristics that might be related to abundance.

Biological sampling required for target strength determination was accomplished through observer and port sampling of purse seine vessels and dockside sampling of gillnet catches in the commercial fishery and from experimental gillnets of varying mesh size. These procedures are described below.

Calibration of the acoustic systems as a prelude to echo-integration, was accomplished using procedures similar to those employed on research vessels conducting acoustic surveys in the southern Gulf of St. Lawrence. The calibration procedure used for vessels in the southern Gulf of St. Lawrence has been described elsewhere (Clay and Claytor 1998) and only a brief overview is provided here.

5.2 Background on fleet acoustic data collection

The development of this project began by conducting qualitative surveys during the fall of 1994 and 1995 in western Prince Edward Island. Regular systematic transect surveys, using inshore boats, were conducted in this area after the fishing season to determine if large schools of herring remained in the area late in the year and to determine the feasibility of conducting assessment surveys using small inshore boats. These surveys consisted of on-board observers making notes on the size of schools and plotting them on survey maps. No attempts at biomass estimation were made. While herring schools observed were small, these projects demonstrated the ability of small boats to conduct surveys and indicated that efforts to collect quantitative data from small inshore boats during regular fishing activity and surveys was warranted. Experiments on the quantitative collection of acoustic data from fishing vessels in the southern Gulf of St. Lawrence began in 1995 (Claytor et al. 1999). In that year, data were successfully recorded from a herring purse seiner during fishing activity in Chaleur Bay and Cape Breton (4Vn) from Aug. 23 to Nov. 24, 1995. Acoustic data were collected using an automated system similar to that used on the southern Gulf of St. Lawrence annual acoustic surveys. The digitizing system, in this case, was attached to a 50khz Furuno FCV120 sounder that was donated by the purse seine captain. The system on board the purse seiner was completely automated and only required the captain to turn the system on to begin recording and to turn it off when the trip was completed.

Quantitative data collection from inshore boats was not as easy to develop. Sounders normally used by inshore vessels did not have data ports and it was not possible to use these systems directly. In addition, fishing captains wanted to retain the ability to adjust the gain setting on their sounders. However, because calibrations (see below) are completed at fixed gain settings, changing the gain requires a new calibration. Hence, it was desirable, as was done on the purse seiner, to have a second sounder on board these vessels that could be calibrated, collect data, and not be adjusted during fishing activity. Because these systems were not available during the first year, 1995, it was possible to only collect navigation data from the vessel participating in the project. This collection occurred in Chaleur Bay during September (Claytor et al. 1995; Claytor et al. 1999).

The second year of the project, 1996, concentrated on developing a system that could be used to collect data from inshore vessels, testing survey methods for these vessels, and developing analytical tools. Automated systems were placed on two purse seiners fishing in Chaleur Bay and 4Vn and two inshore vessels fishing in Chaleur Bay. Data collection from the purse seiner, 'Gemini' was successful but the spare commercial sounder on the second purse seine vessel, 'Ocean Leader', was more difficult to maintain. Commercial sounders at 200kHz were purchased for the gillnetters and data were collected successfully from each of these vessels. Successful ball and time varied gain calibrations were completed on only one of the inshore boats. Poor weather prohibited a calibration on one of the seiners, and equipment problems precluded calibration on the other two vessels.

Experience from these first two years indicated that development of separate sounders with an intermediate frequency range and use of standard transducers would improve data collection. Developing a stand alone system would provide consistency of equipment between vessels and make calibrations easier. In addition, a frequency intermediate to those used in the fishery would prevent interference on the automated recordings.

The third year of the project, 1997, consisted of collecting data from additional areas of the southern Gulf of St. Lawrence. The intent was to determine the practical difficulties that would result from collecting these data simultaneously over a number of areas. It would also allow a field test of the portable acoustic system developed for this project by Femto Electronics. The work with the 'Gemini' was continued as before using its spare commercial sounder. Acoustic recorders at 120 kHz were placed on six inshore boats, two each from West PEI, Escuminac, and Gulf Nova Scotia. Successful ball and time varied gain calibrations were completed on all vessels. Data were collected during fishing activity by the purse seiner, two boats from Gulf Nova Scotia, and one each from Escuminac and West PEI. The purse seiner in 4Vn, two boats from Escuminac and two from Gulf Nova Scotia conducted surveys. No surveys were conducted in West PEI.

In 1998, data collection during the fall season was restricted to two inshore boats fishing in the Gulf Nova Scotia area and the 'Gemini'. These data collections were repeated in 1999, but with the addition of a switch placed on one of the gillnetters that would record when the winch for hauling the net was being operated. This addition is being tested to determine if more precise information on hauling and set time could be collected, which could be used in speeding up the data editing process. As a result, the data base is much larger than that presented here and additional analyses are possible (Fig. 17).

5.3 Data preparation

The data used in the analysis presented in this thesis comes from the 1997 Gulf Nova Scotia inshore and the 1995 purse seine data collections (Figs. 18, 19). These data sets represent the first year for data collection in each of these areas, which has continued through to 1999. The boat used in the analysis of the Gulf Nova Scotia data is the 'Broke Again' and has been a consistent participant in the project from 1997-1999. The purse seine vessel is the 'Gemini' and has been a consistent participant from 1995-1999.

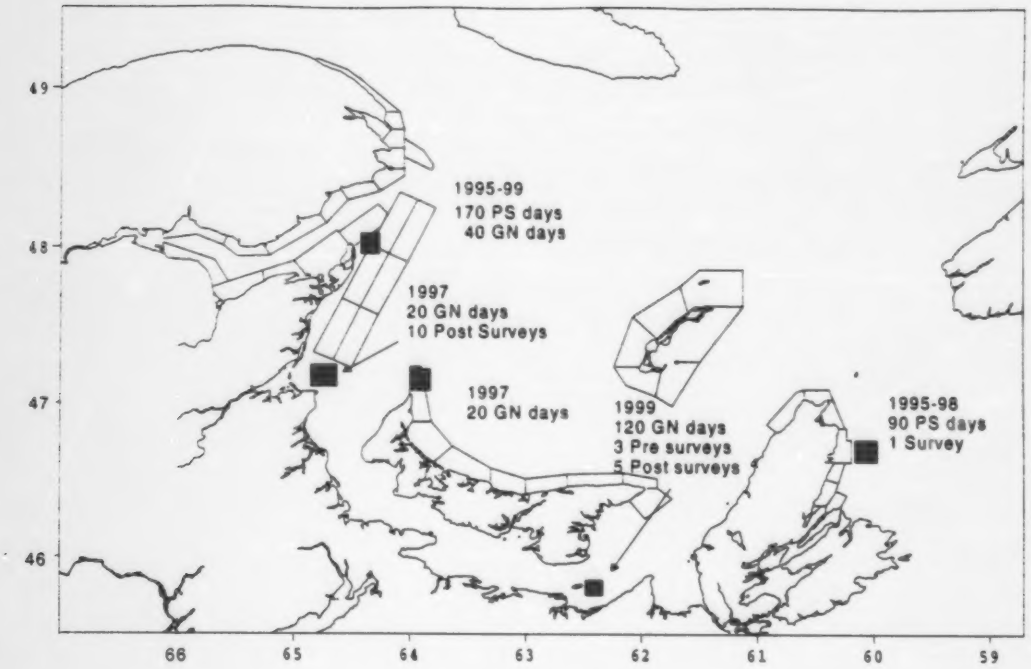

49
48
47
46
66
65
64
63
62
61
60
59
1995-99
170 PS days
40 GN days
1997
20 GN days
10 Post Surveys
1997
20 GN days
1999
120 GN days
3 Pre surveys
5 Post surveys
1995-98
90 PS days
1 Survey

Fig. 17. Location of acoustic research survey strata (boxes) and fleet acoustic projects for southern Gulf of St. Lawrence herring. PS, purse seiners; GN, gillnetters. Days refer to number of days of data collected during regular fishing activity and surveys.

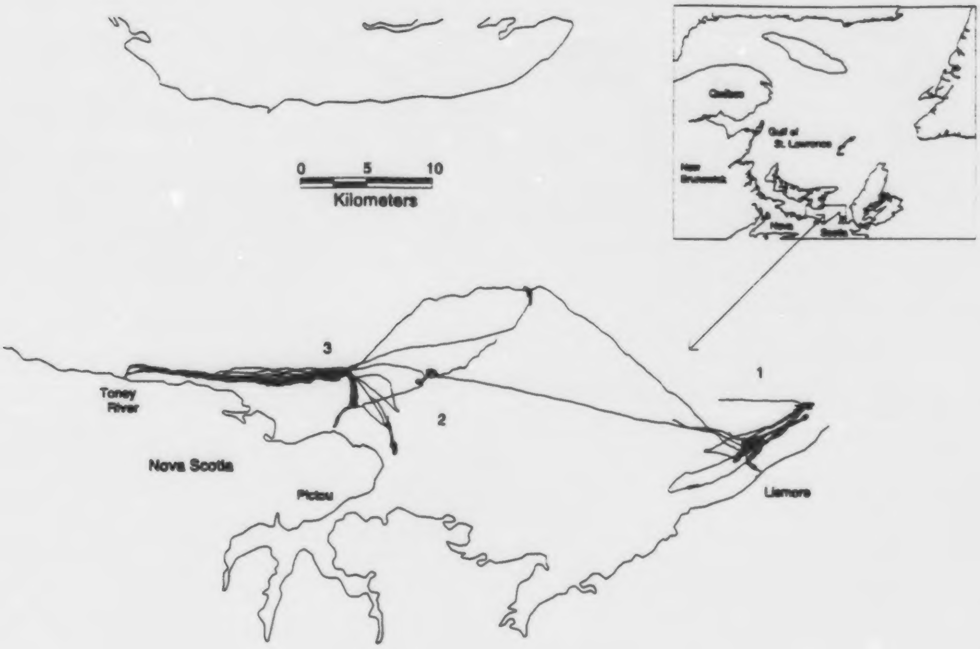

0
5
10
Kilometers
Québec
Gulf of
St. Lawrence
New
Brunswick
Nova
Scotia
3
1
Toney
River
2
Nova Scotia
Pictou
Lismore

Fig. 18. Fishing and searching tracks for Pictou area gillnetter, 'Broke Again', collecting acoustic data from 7 - 30 September, 1997. Numbers represent three fishing areas: 1, Eastern area; 2, Mid-zone; 3, Western area.

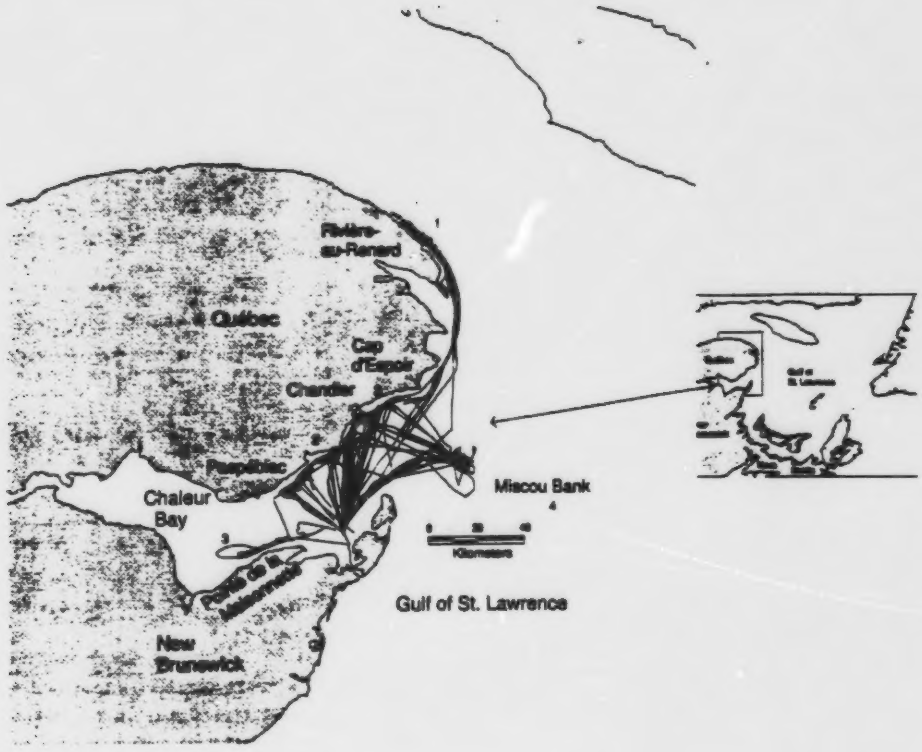

Rivière-au-Renard
1
Québec
Cap d'Espoir
Chandler
2
Paspébiac
Chaleur Bay
3
Pointe de la Maisonnette
New Brunswick
Miscou Bank
4
0
20
40
Kilometers
Gulf of St. Lawrence

Fig. 19. Fishing and searching tracks for purse seiner, 'Gemini', collecting acoustic data from 23 August - 20 October, 1995. Numbers represent four fishing areas: 1, Rivière-au-Renard; 2, Gaspé; 3, Pointe de la Maisonette; 4, Miscou Bank.

5.4 Calibration

Acoustic backscatter is converted to biomass using a target strength per kilogram (TS/kg) relationship that is normally extracted from the literature (Foote 1987) rather than estimated for each individual survey. Using a constant target strength relationship means that, providing the backscatter can be accurately determined, the biomass indices will be comparable over time and among vessels. To optimize the precision of the backscatter estimates it is necessary to do a complete system calibration of the acoustic hardware prior to each survey year. This calibration is important because errors in the calibration parameters have a direct effect on biomass estimates.

All data collection and processing for these calibrations were done using the Femto Hydroacoustic Data Processing System (HDPS). This system consists of software for the collection, integration, and coding of fishing activity, and the hardware consists of a digitizer-sounder, computer and transducer. It is the software and hardware system used on all fishing vessels collecting acoustic data in the southern Gulf of St. Lawrence (Claytor et al. 1998b, 1999). It has also been used on fishing vessel surveys of herring stocks in Atlantic ocean coastal waters of Nova Scotia, Canada (Melvin 1998a,b), Newfoundland, Canada (Wheeler et al. 1999), and the eastern United States (Yund 1998). Fishing vessels have also been used to collect acoustic data on groundfish such as cod in Newfoundland (Anderson et al. 1998) and rockfish in British Columbia, Canada (R. Kieser, pers. comm., Department of Fisheries and Oceans, 3190 Hammond Bay Road, Nanaimo, British Columbia, V9R 5K6). The software and hardware has been used on research vessel acoustic surveys in several areas, including the southern Gulf of St. Lawrence (Clay and Castonguay 1996, Claytor et al. 1999).

Once in place, two standard calibrations were performed for each system installation:

1. Time varied gain (TVG) calibration - Each sounder has a TVG to adjust the gain of the received echo signal to account for losses due to attenuation and absorption. The TVG calibration accounts for the errors in the implementation of this curve.
2. Ball calibration - This calibration is used to adjust the fixed gain of the TVG curve using one known datum point, the echo return from a calibration sphere having a known target strength (TS).

The order of these calibrations is not important but the ball calibration is normally done at the beginning of the season. However, this calibration may be postponed until a later date during or just after the fishing season due to weather and vessel scheduling constraints. The TVG calibration can be done while the vessel is tied to the wharf and therefore is less constrained by vessel use and weather. All calibrations must be done before any biomass estimates are produced.

The acoustic system employed on the gillnet boat 'Broke Again' consisted of a 120 kHz transducer with a 14° beam angle, a transceiver (Femto DE9320 Digital Echosounder), and a computer for logging data. The digitizing system (Femto) used on the purse seiner was identical to that used during acoustic research surveys in the southern Gulf of St. Lawrence (Claytor and LeBlanc 1999) and was attached to a 50KHz Furuno FCV120 sounder. These systems are analogous to a black box on an airplane in that the captain of the vessel turns the unit on when leaving port and off when returning and digital acoustic data is continually recorded during the fishing trip (Claytor et al. 1999).

The ball calibration was completed by suspending a 38.1 mm tungsten-carbide sphere directly below the transducer on the acoustic axis using a three point suspension system employing extendible aluminum rods and fishing reels. The calibration routine computed the uncalibrated sphere target strength (TS) and determined the necessary correction required to equal the theoretical TS. The desired sphere depth for the calibration was approximately 10 metres below the transducer.

The TVG calibration was accomplished by applying a dummy load, which simulates the presence of a transducer, to the transceiver and sending a known continuous wave signal into the receiver while recording the output as if it were a normal acoustic data collection. The parameters of the TVG curve were estimated and incorporated into TS processing from the ball calibration (Clay and Claytor 1998). All hardware and software settings and equipment that applied during the calibration remained constant during the data collection (see also Claytor and Clay 2001).

The results of the calibration are used to convert acoustic signal strength to density (kg/m^2) at each navigation point (MacLennan and Simmonds 1992). Calibrations of acoustic equipment on inshore boats provided comparable results to those of research vessels (Clay and Claytor 1998).

5.5 Biological sampling - Target strength

The next step in the analysis was to determine TS for each night of interest so that the backscatter coefficients can be converted to density estimates. This procedure begins with the collection of biological samples to determine length - weight relationships. For the inshore gillnet samples this collection was made using variable size gillnets that included mesh sizes smaller and larger than the commercial fishery as described below. These nets were required because of the size selective nature of the commercial gillnets (Claytor and LeBlanc 1999). As expected, younger ages were caught in smaller mesh sized nets (Fig. 20). As a result, the data used for target strength determination included lengths and ages that would not have been included if commercial landings alone were used (Fig. 21).

The experimental nets consisted of six panels of the following mesh sizes: 2", 2 1/4", 2 1/2", 2 5/8", 2 3/4" and 3". Each panel, after hanging at the head rope, was 8 feet long and 16.5 feet deep regardless of mesh size. A distance of three feet separated each panel from the other. Mesh material was green knotted nylon. Net strings used in Pictou, Nova Scotia were made at the Nova Scotia School of Fisheries. Each of the boats equipped with the acoustic recorders tried to fish these nets once a week during the fishery. All mesh sizes were successfully fished on three occasions by one boat, September 4, 18, and October 10. The second boat fished only the 2" and 2 1/4" mesh. Mesh sizes used in the inshore fishery were primarily 2 5/8" and 2 3/4".

Samples from September 18 in Gulf Nova Scotia were used for all target strength determinations for inshore boats. This date was chosen because it was the closest in date to all inshore data sets presented in this chapter, and was the only one taken during the commercial fishery. The September 4 sample was taken before the fishery began and was on a very small school. The October 10 sample was taken during a survey after the season. The procedure was to add the numbers-at-length for each mesh size to determine an overall catch at length for the population (Fig. 22).

For the purse seiner, sampling and length frequency distributions from observer on-board samples were used to determine target strength (Fig. 23, Table 4).

TS/kg was estimated using the relationship determined by Foote (1987). The formula is:

$$TS_{log} = (20\log_{10} l - 71.9) - 10\log_{10} w \qquad (8)$$

where TS, target strength; *l*, length (cm); and *w*, weight (kg).

The steps for determining target strength are:

1. Determine the length-weight relationship from the samples that are most relevant to the acoustic signal being estimated. These are obtained using the detailed samples that consist of two fish from each 0.5 cm group that were retained for aging, maturity stage, length, and weight analysis. A weight-length regression is used to obtain the slope and intercept values that can be used to estimate weight as:
2.

$$w = al^b \qquad (9)$$

$$\text{or } \log_{10} w = \log_{10} a + b\log_{10} l$$

where $\log_{10} a$ =intercept and b =slope of weight-length regression.

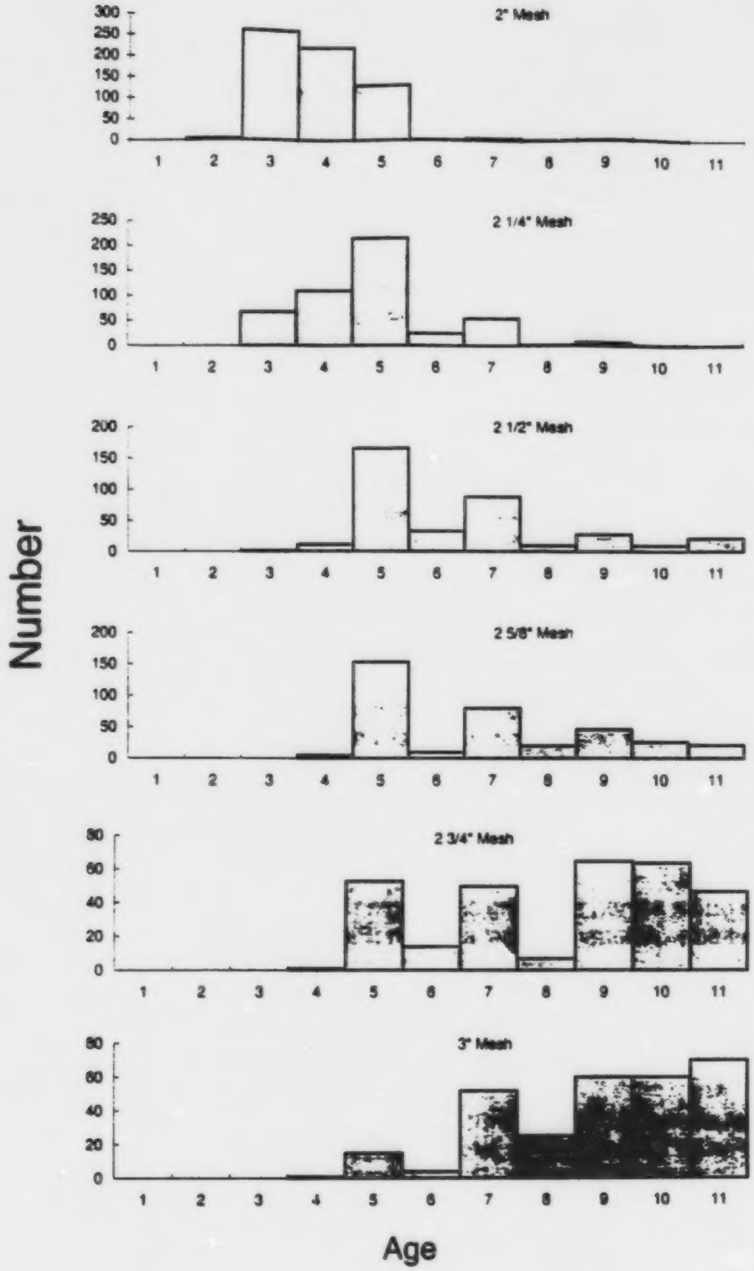


Fig. 20. Numbers-at-age from Pictou, Nova Scotia experimental gillnets, 1997.

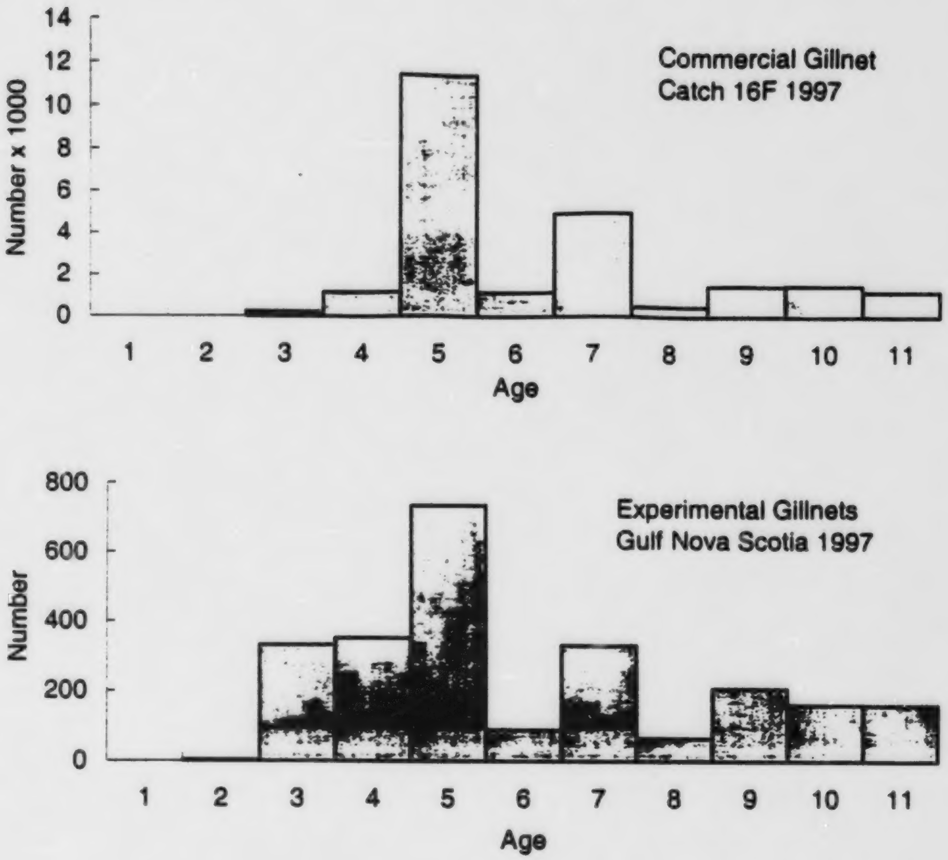


Fig. 21. Numbers-at-age in experimental nets, all sizes combined, and commercial gillnet fishery in Pictou, Nova Scotia, 1997.

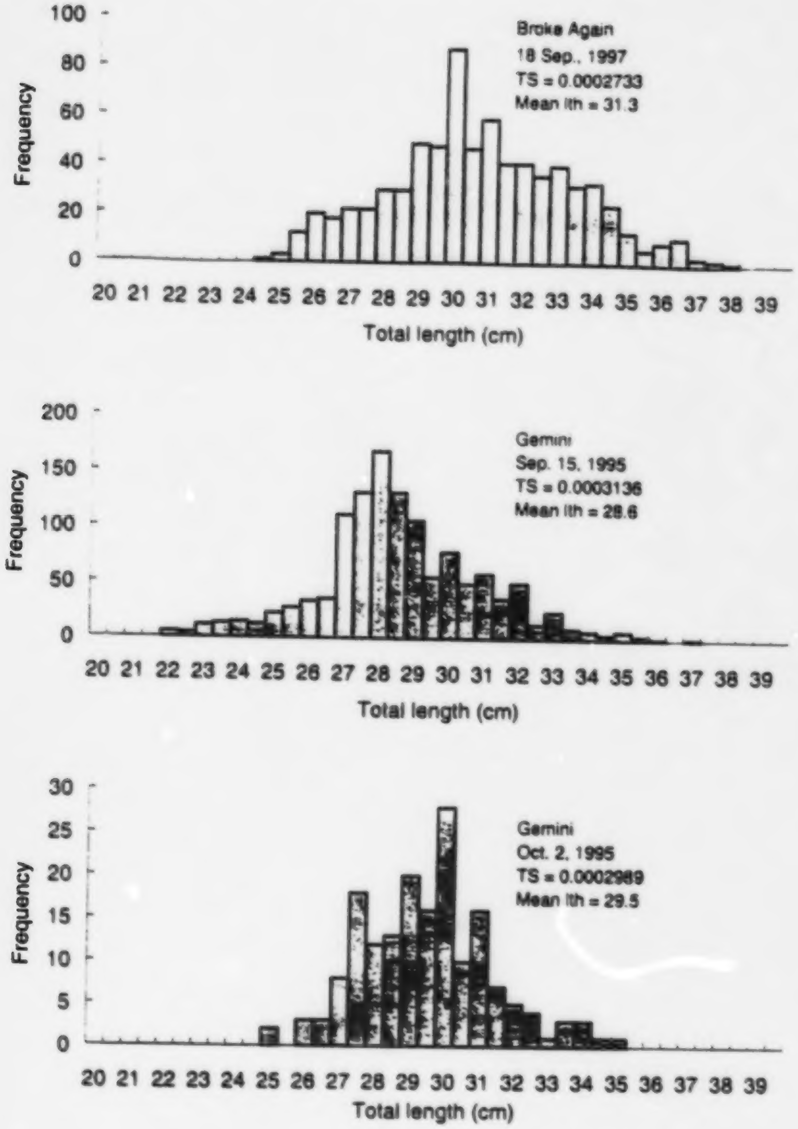


Fig. 22. Length frequency distribution from gillnet experimental net sampling (top) and examples of length frequency distributions from purse seine sampling (middle and bottom). Length frequency distributions were used to determine target strength of acoustic samples. TS = target strength; lth = length.

Table 4. Summary of daily length distributions from purse seiners fishing in Chaleur Bay during the fall season in the southern Gulf of St. Lawrence, 1995.

Date Landed	Total Length (cm)		
	% ≤ 26	% 26-30	% > 30
22 Aug	0	28	72
24 Aug	0	23	77
27 Aug	1	72	27
28 Aug	0	66	34
29 Aug	0	63	37
30 Aug	2	53	45
31 Aug	3	51	46
1 Sep	0	61	39
2 Sep	1	68	31
3 Sep	1	50	49
4 Sep	0	52	48
5 Sep	1	41	58
7 Sep	0	66	34
8 Sep	1	80	19
9 Sep	3	85	12
12 Sep	4	67	12
13 Sep	5	56	39
14 Sep	5	74	21
15 Sep	11	67	22
16 Sep	6	69	25
19 Sep	4	66	30
20 Sep	5	56	39
21 Sep	3	74	23
22 Sep	6	66	28
24 Sep	5	60	35
25 Sep	3	82	16
26 Sep	1	72	27
27 Sep	3	72	25
28 Sep	4	74	22
30 Sep	5	78	17
2 Oct	5	59	36
3 Oct	2	55	43
4 Oct	1	64	34
5 Oct	4	74	23
6 Oct	5	83	12
10 Oct	8	74	18
11 Oct	0	73	26
12 Oct	9	76	15
13 Oct	2	76	21
14 Oct	0	63	37
15 Oct	0	84	16
16 Oct	0	64	36
18 Oct	9	86	5

3. Obtain the length frequency distribution(s) from the sample of interest, weighting them by catch if more than one is used.

4. Use the weight-length regression to estimate weight for each length interval in the length frequency distribution.

5. Estimate TS using Foote's (1987) formula (8) and linearize using the dB formula given by MacLennan and Simmonds (1992).

$$TS_{lin} = 10^{\left(\frac{TS_{log}}{10}\right)} \tag{10}$$

6. Determine the frequency distribution of the target strengths and decide if the mean or the mode most appropriately describes the distribution.

7. Linearize the area backscatter coefficient (Sa) using the MacLennan and Simmonds (1992) dB formula:

$$Sa_{lin} = 10^{\left(\frac{Sa_{log}}{10}\right)} \tag{11}$$

8. Estimate the ρ (density in kg/m^2) by:

$$\rho = \frac{Sa_{lin}}{TS_{lin}} \tag{12}$$

5.6 Fishing activity

Recording latitude and longitude identified the fishing track once per second using Garmin 45XL portable GPS units. The acoustic signal at every fourth navigational position fix was retained to determine biomass density along the fishing track. Selection at every fourth fix was done to reduce the size of the data set and to remove small fluctuations in the fishing track because of errors in GPS satellite signals. The activities along each fishing track were defined as:

1. Traversing: time and distance from port to fishing grounds for inshore boats and purse seiners.
2. Searching: time and distance spent searching for schools of fishable size on the fishing grounds.
3. Fishing (Purse Seiner): For purse seiners fishing activity has been divided into sets (time and distance spent setting the net) and pumping (time and distance spent pumping the catch into the boat).
4. Fishing (Gillnetter): For the inshore gillnetters, fishing includes the time and distance spent setting the net, soak time for the net, and hauling the net. It is difficult to separate these activities for the gillnetter because, unlike the purse seiners, the gillnet track pattern during hauling closely resembles that during setting.

After coding for fishing activity the fishing track data were divided into 100m increments by fishing activity. The end of the fishing track in each activity, however, would usually be <100m. A distance weighted average of the biomass densities along the 100m interval was calculated. This calculation was made by multiplying the distance traveled associated with density estimate and dividing the sum of these values by the length of the interval; usually 100m, or less at the end of a segment. This datum point became the center point of the interval (Figs. 23, 24).

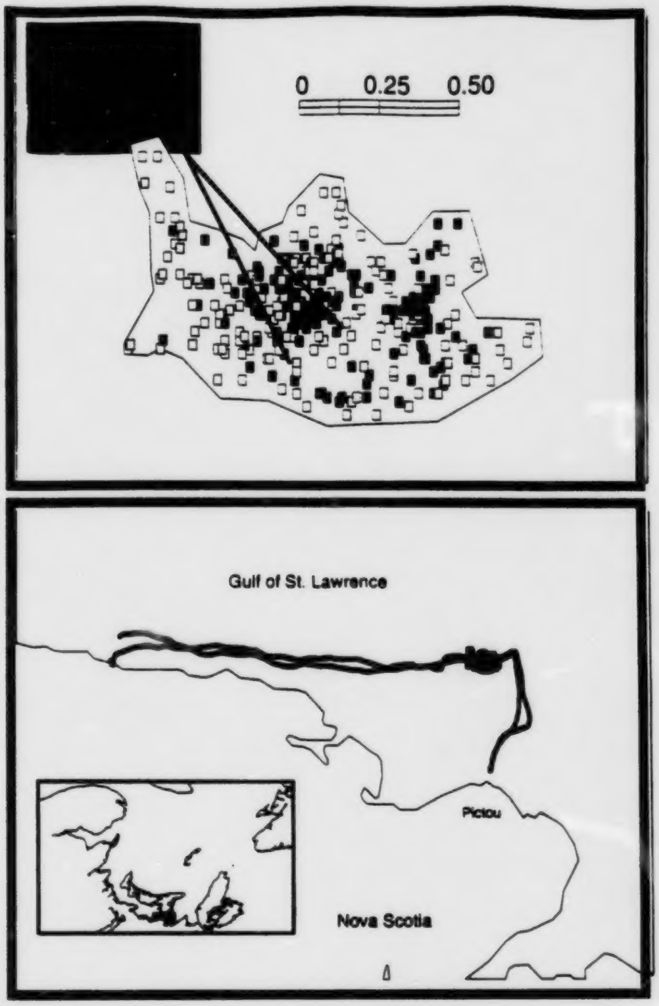

0
0.25
0.50
Gulf of St. Lawrence
Pictou
Nova Scotia

Fig. 23. An example of how the fishing and searching track from the gillnetter data collection was divided into 100m increments. This example is from Pictou, Nova Scotia, 26 September 1997. An example of the echogram is shown, search area for estimation is indicated by polygon. Solid squares ≥ 0.0625 kg/m^2, open squares < 0.0625 kg/m^2. Lines from echogram indicate extent of the fishing track displayed in the echogram (1.1 km).

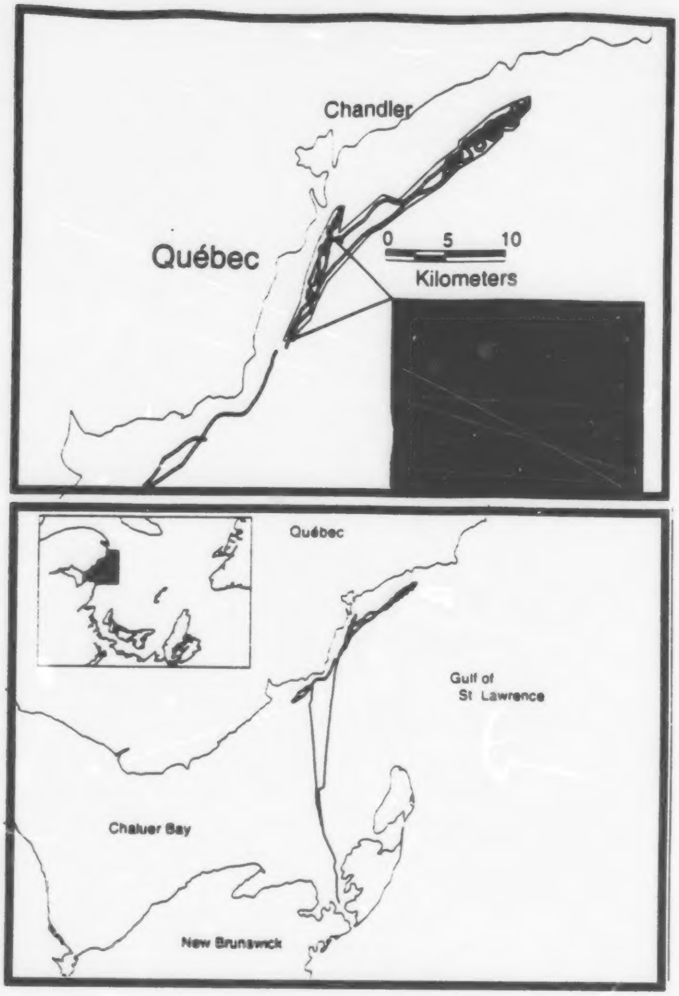

Chandler
Québec
0 5 10
Kilometers
Québec
Gulf of
St Lawrence
Chaluer Bay
New Brunswick

Fig. 24. An example of how the fishing and searching track from the purse seine data collection was divided into 100m increments. This example is from Chaleur Bay, 2 September, 1995. An example of the echogram is shown, search area is indicated by polygon. Solid squares ≥ 0.0625 kg/m^2, open squares < 0.0625 kg/m^2. Lines from echogram indicate extent of the fishing track displayed in the echogram (6.3 km).

5.7 Spatial analysis - Data

Only the portion of the fishing track associated with searching and setting the net (see above) was selected for spatial analysis. Searching was generally triggered at densities ≥ 0.0625 kg/m^2 or about 1/4 herring/m^2, and setting the net occurred only in areas that had been searched. Hauling (gillnetters) and pumping (purse seiners) was always associated with setting the net, but this activity created a lot of debris in the water and these data were not suitable for biomass estimation and were eliminated. A polygon drawn around the boundary of the searching and setting data points defined the area for spatial analysis and biomass estimation (Fig. 23, 24). The density estimate used in all analyses was the biomass estimate within the polygon divided by the area of the polygon. The next step in preparing the data for biomass estimation was to aggregate identical data points. Averaging all points that were within one metre of each other to form a new datum point completed this aggregation. All mapping, data selection, and aggregation were done using MAPINFO (1997) and VERTICAL MAPPER (1998) routines.

5.8 Inverse distance weighting (IDW)

Inverse distance weighting (IDW) is an interpolation method that gives more weight to the closest samples and decreasing weight to samples that are further from the estimation point. VERTICAL MAPPER (1998) was used to estimate biomass by this method. The cell size was 10 metres and search and display distances were the defaults, based on a percentage of the total map area, and provided by the software. The exponent that described the decay of influence between points was kept at the default of 2. A maximum of 25 points was analyzed for each grid node. The number of zones and the minimum number of points were kept at 1. Inverse distance weighting provides maximum estimates below and minimum estimates above those observed.

5.9 Voronoi - Natural neighbor analysis

Voronoi polygons or Dirichlet tessellations (Green and Sibson 1978; Boots and Murdoch 1983; Byers 1992) were used to derive biomass indices from the acoustic data collected during regular fishing activity. A voronoi polygon is one that surrounds an observed datum point, P, such that any other point, x_i, that may reside within the polygon is closer to P than any other observed point outside the polygon, x_o. They are related to Delaunay triangles in that the circle that circumscribes a Delaunay triangle has as its center the vertex of a voronoi polygon (Preparata 1985; Watson 1992).

VERTICAL MAPPER (1998) builds these regions around data points using Delaunay triangulation. The network of polygons generated is called a voronoi diagram. The area of the region or polygon is then the weight for the point. The voronoi-natural neighborhood method maintains observed maximum and minimum values.

5.10 Arithmetic

The arithmetic method assumes that all points have equal weight in the estimation and is simply the arithmetic average of all the points within the polygon.

5.11 Kriging

Kriging includes a group of methods of obtaining global or point estimates from spatial data such that points nearest the point of interest receive the highest weight and those most distant receive the least weight. Ordinary kriging assigns these weights by taking into account spatial correlations inherent in the data. For example, regarding fish schools, we expect that points of high density would be clustered together and have similar densities and that points further away would be less similar. Thus, the points closest to the area we are trying to estimate should receive the greatest weight in the estimation, and those further away, the least weight.

These weights are linear combinations of the available data and are dependent on the variogram model (Clark 1979; Isaaks and Srivastava 1989).

The spatial relationship is determined by examining the correlation among data points at progressively greater separation distances, until no correlation or relationship is observed. A model is then fit to these relationships and is used to estimate points or blocks without sampling.

In kriging the correlation among the points is described by a variogram model. The parameters that characterize the variogram are:

1. The range: the distance beyond which there is no correlation between pairs of data points.
2. The nugget effect: the discontinuity of the variogram model at the origin (zero sample separation). This value should be zero, but sampling error and short scale variability (at sample separation less than the minimum data spacing) causes a jump in the relationship for short distances.
3. The sill: the variance in the data as measured by the height at which the variogram reaches a plateau.

Several types of models can be used to approximate experimental variograms based on real data, among them are spherical, exponential, and gaussian models. The spherical model is widely used and was applied in this analysis and this model produced reasonable variograms. Directionality (anisotropy) is also a feature that is present in some spatial data. The kriging modeling and examination of the data for directionality is described below.

The first step in the kriging analysis was data exploration to provide a basis for making decisions on initial lags for variograms and assist in interpreting the reliability of final results. Initial lags were chosen using the average distance between data points (Table 5) and the pattern observed from variogram cloud scatterplots. Variogram cloud scatterplots consist of the squared difference between density values for each point plotted against distances between each point. Patterns in these values would indicate appropriate choices for initial variogram lags (Armstrong 1984). Density contour plots from the raw data and density frequency distributions were used to insure that kriging results provided reasonable estimates. Examples of variogram clouds, contour plots, and density frequency distributions (Figs. 25, 26, 27) indicate the variation in some of these patterns and in kriging results. Complete kriging analyses are presented for each day analyzed in Appendix 1.

Table 5. Summary statistics for gillnet and purse seine data used to investigate differences among kriging, voronoi, inverse distance weighting, and arithmetic biomass estimation methods. Gillnet data are from 1997 and purse seine data are from 1995. STD = standard deviation.

Date	Region	Start Time	End Time	No. Obs	Min. Density	Max. Density	Ave. Density	STD Density	Ave. Distance
Gillnet									
7-Sep	1	23.05	26.48	160	0.00	30.82	4.26	5.07	30.49
7-Sep	1	29.01	30.93	66	0.00	48.84	8.11	10.53	34.25
8-Sep	1	26.38	29.22	174	0.00	0.97	0.15	0.22	43.52
9-Sep	1	20.02	22.69	128	0.00	4.82	0.60	0.94	26.50
9-Sep	2	27.42	28.69	53	0.00	8.97	1.19	1.69	30.61
9-Sep	3	25.46	29.86	40	0.00	0.92	0.21	0.24	39.46
10-Sep	1	20.03	25.18	294	0.00	8.57	0.41	0.99	39.91
11-Sep	1	20.11	24.35	194	0.00	8.91	0.53	1.08	34.42
11-Sep	2	25.80	31.27	151	0.00	23.43	3.52	5.66	22.78
16-Sep	1	23.56	32.39	166	0.00	42.99	6.47	8.39	28.88
16-Sep	2	20.40	21.31	75	0.00	6.21	0.17	0.84	68.52
17-Sep	1	21.15	24.82	103	0.00	42.99	6.43	8.22	35.58
19-Sep	1	0.84	2.50	127	0.00	8.98	0.31	1.06	41.60
19-Sep	1	5.02	6.34	101	0.00	8.38	0.47	1.33	42.23
22-Sep	1	19.59	21.90	67	0.00	11.79	0.60	1.99	27.70
22-Sep	1	19.48	24.89	123	0.00	27.64	0.90	3.28	64.50
23-Sep	1	15.83	16.91	27	0.00	83.82	15.14	22.32	24.48
25-Sep	1	1.25	8.56	84	0.00	80.05	7.05	14.59	73.52
25-Sep	2	2.41	5.19	57	0.00	68.13	9.44	16.27	40.42
26-Sep	1	15.96	17.92	117	0.00	73.01	8.65	16.61	37.09
26-Sep	1	18.50	19.95	53	0.00	91.91	10.19	20.08	53.81
28-Sep	1	18.63	20.42	83	0.00	48.23	5.67	8.88	27.43
28-Sep	2	25.38	25.58	20	0.00	87.77	18.57	30.14	76.51
29-Sep	1	18.66	19.19	20	0.00	2.84	0.25	0.71	40.64
29-Sep	2	19.32	21.78	111	0.00	35.76	3.79	5.90	27.78
30-Sep	1	19.39	21.27	121	0.00	91.91	8.92	14.98	40.25
Purse Seine									
23-Aug	1	25.01	28.35	300	0.00	15.30	0.59	1.96	106.00
28-Aug	1	23.63	24.60	147	0.00	6.60	1.20	1.31	116.00
14-Sep	1	25.61	28.85	366	0.00	11.80	1.07	1.34	78.80
14-Sep	2	22.48	25.24	51	0.00	4.10	1.37	1.46	110.00
15-Sep	1	20.98	21.44	26	0.51	6.82	3.31	1.92	70.90
15-Sep	2	25.35	29.66	526	0.00	8.39	1.20	1.22	78.90
26-Sep	1	20.39	22.86	70	0.01	4.61	1.09	1.42	89.30
26-Sep	1	27.59	27.92	43	0.00	6.51	1.52	1.84	100.00
26-Sep	2	27.00	27.30	32	0.00	4.20	0.38	1.02	86.50
26-Sep	3	23.29	26.91	178	0.00	4.61	0.79	0.99	88.30
27-Sep	1	24.27	29.15	160	0.00	7.23	0.88	1.35	79.60
27-Sep	2	29.33	29.49	22	0.38	6.15	2.76	1.75	100.00

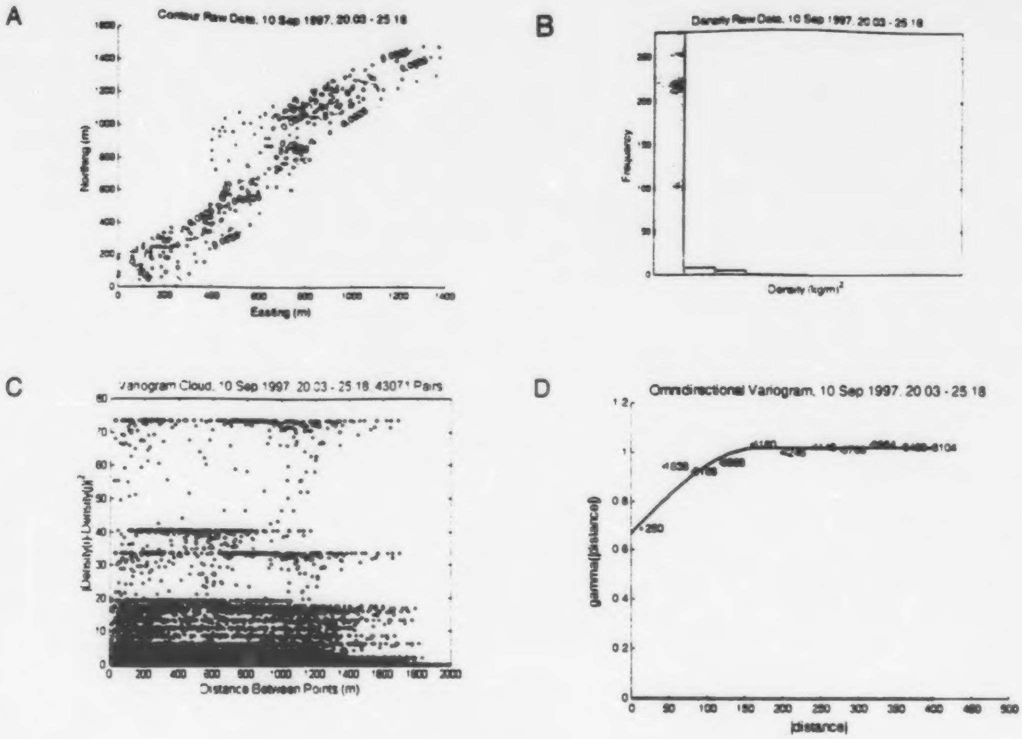
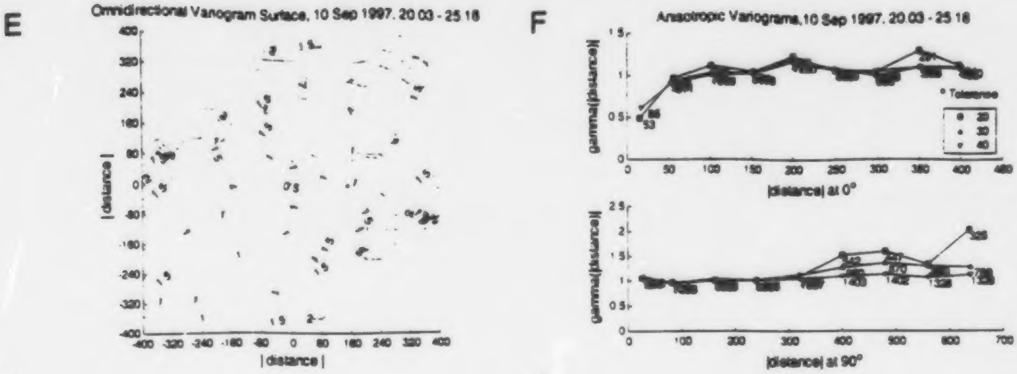


Fig. 25. Components of block kriging analysis for gillnetter data 10 September 1997, region 01, between 20.03 - 25.18. Data pertains to an individual region fished on the given night and as a result, times are not continuous. (A) Contour plot of data to identify high and low density areas. (B) Histogram of density distributions to determine if there are any distributional effects to consider in the analysis. (C) Variogram cloud to identify any patterns that should be considered for initial lags. (D) Initial omnidirectional variogram to provide basis for investigating anisotropy. Components E-H continued on next page.



G

H

Fig. 25. (cont.) (E) Omnidirectional varigram surface to identify possible anisotropic effects. (F) Anisotropic variograms to assist in anisotropic modeling if required. (G) Modeling the anisotropic variograms was not required for these data. (H) Relative densities for block kriging estimate using most appropriate variogram model. Variogram surface and variograms indicated that an omnidirectional variogram was suitable for this analysis.

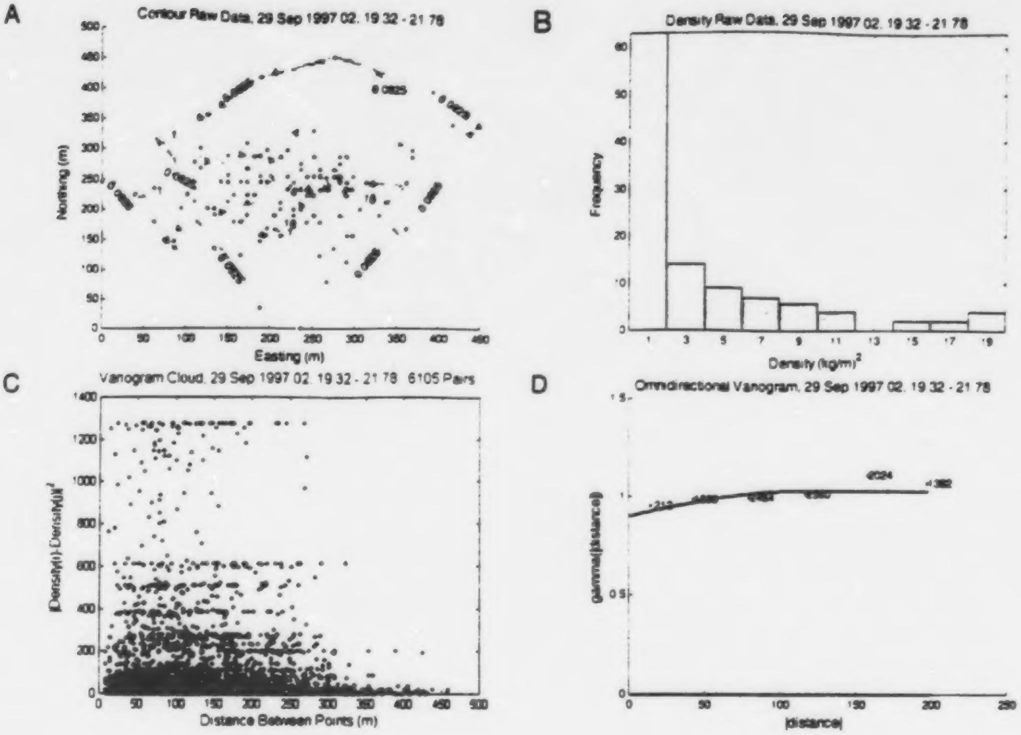


Fig. 26. Components of block kriging analysis for gillnetter data 29 Septempber 1997, region 02, between 19.32 – 21.78. Data pertains to an individual region fished on the given night and as a result, times are not continuous. See Fig. 25 for explanation of components. Components E-H are continued on next page.

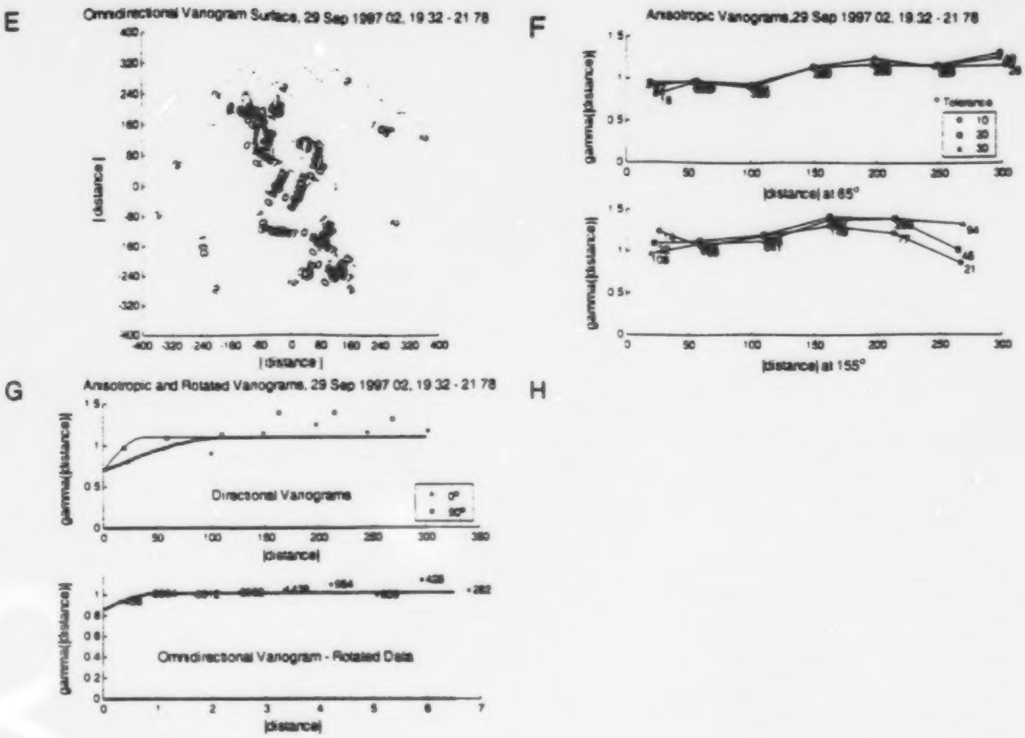


Fig. 26. (cont.) See Fig. 25 for explanation of components. Variogram surface and variograms indicated that an aniostropic variogram was suitable for this analysis.

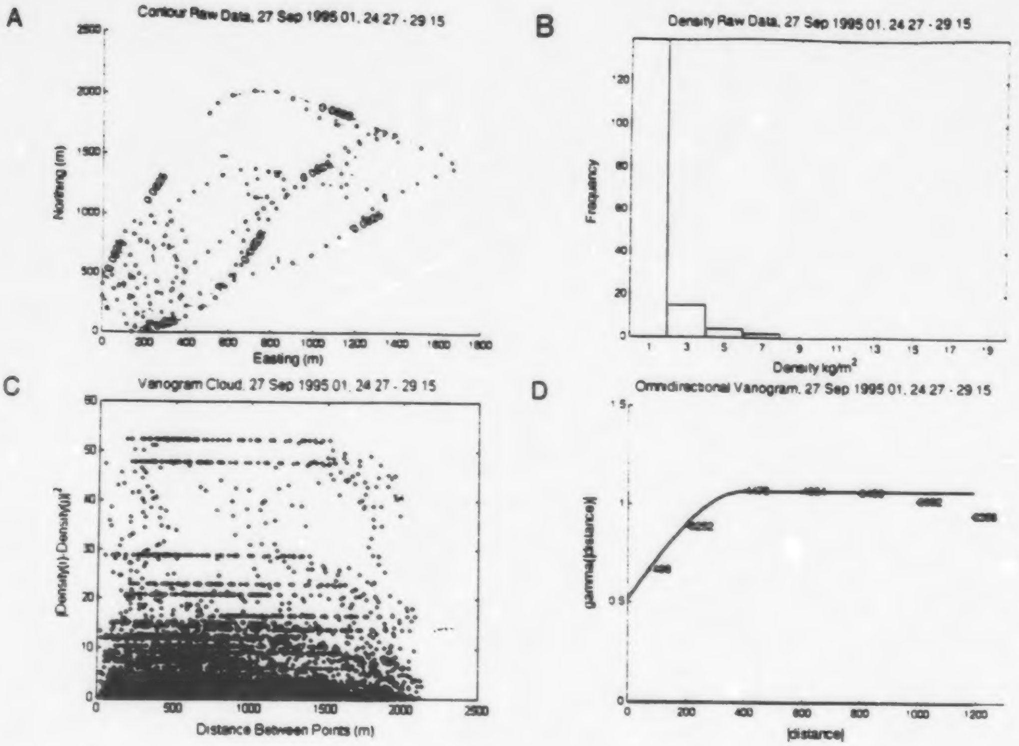


Fig. 27. Components of block kriging analysis for purse seiner data 27 September 1995, region 01, between 24.27 - 29.15. Data pertains to an individual region fished on the given night and as a result, times are not continuous. See Fig. 25 for explanation of components. Components E-H are continued on the next page.

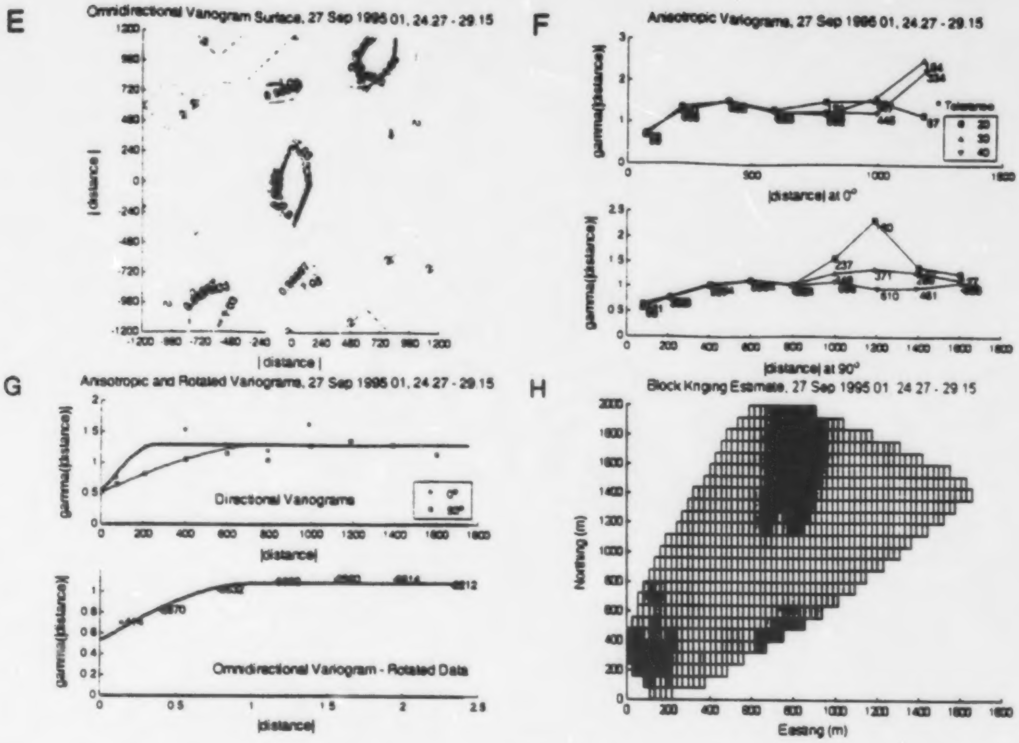


Fig. 27. (cont.) See Fig. 25 for an explanation of components. Variogram surface and variograms indicated that an anisotropic variogram was suitable for this analysis.

The next step in the kriging analysis was to find the best omnidirectional variogram. Average and standard deviation of densities were correlated (Table 5). As a result, relative variograms as described by Isaaks and Srivastava (1989) and implemented by VARIOWIN (Pannatier 1996) were used to model spatial relationships. The experimental variogram was modeled using a spherical model of the form:

$$\gamma = C_o + C\left[\frac{3}{2}\frac{h}{a} - \frac{1}{2}\left(\frac{h}{a}\right)^3\right] \tag{13}$$

where C_o = nugget; C= sill; h= distance; a= range (Cressie 1991).

A variogram surface was then produced using the lag distances and number determined from the variogram modeling. The same number and distance for lags were used in each of the x and y directions. VARIOWIN (Pannatier 1996) was used to produce these surfaces (Figs. 25, 26, 27; Appendix 1). Orientation of these surfaces was used to investigate anisotropy in the variogram models. Experimental variograms were investigated at each major direction and an angle 90° to the major axis, with angle tolerances of 20°, 30°, and 40°. If directional variograms were identified that had fits which were comparable to the omnidirectional variogram and ranges that differed by direction, anisotropic variograms were modeled. Anisotropic variogram modeling proceeded by first modeling each direction separately assuming geometric anisotropy, or identical sills but differing ranges (Isaaks and Srivastava 1989). This modeling determined the range and anisotropic parameter needed for rotating and transforming the data so that an omnidirectional variogram could be modeled.

The rotational transformation was done using the method described by Isaaks and Srivastava (1989) and produced omnidirectional variograms with a range of 1. Block kriging (Isaaks and Srivastava 1989) proceeded with either the untransformed or transformed and rotated omnidirectional variogram, whichever model was most appropriate (Figs. 25, 26, 27; Appendix 1).

A program written in MATLAB (1998, ver. 5.3) was used to perform the block kriging. Blocks were formed so that each block was less than 1% of the total area to be estimated. The area to be estimated was bounded by the convex hull of the data. As a result, the area of the blocks was always within 5% of the total area of the convex hull and was usually less. Only blocks with centres inside the convex hull were used in estimation. A grid of 4 x 4 points was formed within each block.

The search radius was 2 *x* the range from the centre of the block, with a minimum sample size of 25 required for each estimation. The minimum sample size was lowered to 15 points for data sets that had samples sizes less than 25 (Table 5). If the required number of sample points was not obtained with the initial search radius, then it was doubled until the required number of samples was obtained. This condition rarely occurred. The variogram and block kriging parameters for each day analyzed are given in Appendix 1. If the analysis used a rotated and transformed omnidirectional variogram, the data were converted to their original form for presentation purposes (Figs. 25, 26, 27; Appendix 1).

5.12 Stock assessment parameters

The stock assessment parameters estimated for analysis were: density of the schools on the fishing grounds as defined above, gillnet catch per unit effort (CPUE) defined as kg/net, gillnet and purse seine catch/metre searched with searching as defined above, and an exploitation rate index (ER) defined as the reported catch / biomass estimate of the school that was obtained from the voronoi polygon procedure described above.

The source of catch data for the gillnet fleet was the 100% dockside monitoring program in place in the gillnet fishery in 1997. The number of nets used each night by the 'Broke Again', as reported to us each night by the captain, was five and did not vary. The average number of nets used by all other gillnetters in the area was also five as estimated by a phone survey conducted each year for the annual assessment of this stock (Claytor and LeBlanc 1999). The source of catch data for the purse seiner was the purchase slip sales recorded at dockside. These are reported in Department of Fisheries and Oceans Zonal Interchange Files (ZIF).

5.13 Statistical analyses

Linear and non-linear regression techniques were used to examine the relationships among the four estimation methods, between density and distance searched, and between catch rate indices and density. A p-value < 0.05 was considered significant.

The relationship between CPUE and density was examined using a von Bertalanffy type function and a standard linear regression. A zero intercept was forced in each case because at zero density the catch must also be zero. The von Bertalanffy function followed the additive error structure as defined by Quinn and Deriso (1999) as:

$$CPUE = CPUE_{\infty}\left(1 - e^{-k\rho}\right) + \varepsilon \tag{14}$$

In this form, *CPUE*$_{\infty}$ is an asymptotic value, *k* describes the rate at which the asymptote is reached, ρ is density (kg/m^2), ε is error term.

The linear regression model was defined simply as:

$$CPUE = b\rho + \varepsilon \tag{15}$$

In this form, *b* is the slope of the line and others are as in (14).

A non-linear exponential model (Exp) and linear reciprocal model were used to determine the relationship between density and distance searched on the fishing grounds.

The exponential model was :

$$\rho = b_o e^{b_1 \tau} + \varepsilon \tag{16}$$

where b_o and b_1 are parameters to be estimated and τ is distance (m).

The reciprocal model was:

$$\rho = b_o + \frac{b_1}{\tau} + \varepsilon \tag{17}$$

where parameters are as in equation (16).

The von Bertalanffy and linear models were used to determine the relationship between catch / metre and density as described above for purse seine and gillnet boats.

In these analyses, the density estimated from the data collected by the 'Broke Again' and the 'Gemini' were compared to their individual landings as well as to those of all the boats participating in each of their fleets. Regions for the gillnet fishery are defined as: 1, eastern most zone; 2, mid-zone; and 3 as the western most zone of the Pictou, Nova Scotia fishing area (Fig.18). Regions for the purse seine fishery are defined as: 1, Rivière-au-Renard; 2, Gaspé side of Chaleur Bay, 3, Pointe de la Maisonette; and 4, Miscou Bank (Fig. 19).

5.14 Results - Spatial analysis, catch rates, exploitation rates

Biomass estimates made by each of the four estimation methods were all significantly correlated ($p<0.001$, $r^2 > 0.96$). Differences in estimates were the least between the IDW and voronoi-natural neighbor methods. Differences were greatest for all comparisons with the Arithmetic method (Fig. 28).

Reporting the results of the regression analyses follows the convention that Gillnet Boat refers to catch and effort data only from the 'Broke Again', the gillnetter boat used to collect the acoustic data. All Gillnet Boats refers to catch and effort data from all the boats participating in the Pictou, Nova Scotia fishery. Purse Seine Boat refers to catch and effort data from the 'Gemini', the purse seiner used to collect the acoustic data. Purse Seine Fleet refers to all six purse seine boats participating in this fishery. In each of these cases, the distances searched and the estimated density of schools applies only to the boats collecting the acoustic data, as these data were not collected from any other boats.

The $CPUE_{\infty}$ value for the Gillnet Boat was greater than the $CPUE_{\infty}$ value for All Gillnet Boats. The Gillnet Boat also reached its $CPUE_{\infty}$ asymptote before All Gillnet Boats (Table 6, Fig. 29). Each of the von Bertalanffy model fitting trials converged to a solution, independent of the initial parameter estimates provided to the estimation procedure.

There was a significant curvilinear relationship ($p<0.005$) between density and distance searched on the fishing grounds for the Gillnet Boat and Purse Seine Boat. The fits for the exponential and reciprocal models were similar for each data set (Table 6; Fig. 30).

Linear and von Bertalanffy models significantly explained the relationship between catch / metre and density ($p<0.001$) for Purse Seine and Gillnet Boat models. The linear model provided the best fit for the Purse Seine data and the von Bertalanffy model for the Gillnet data (Table 6; Figs. 31, 32).

The reciprocal model significantly explained the relationship between exploitation rate (ER) and density for the Purse Seine data ($p<0.001$) (Table 6). It indicated that Purse Seine Fleet ER increases rapidly at low densities but is not related to density over most of the range of the data (Fig. 33). The exponential model, which was also significant ($p<0.001$) but had a higher SSR than the reciprocal model (Table 6) indicates there is no relationship between Purse Seine Fleet ER and density (Fig. 33).

The reciprocal model is also the best fit for the All Gillnet Boat ER model. However, both models were significant ($p<0.001$) (Table 6; Fig. 33). Each of these models indicates that ER will increase as density decreases. All ER values that were well above average occurred at below average densities (Fig. 33).

All above average exploitation rates for the Purse Seine Fleet occurred after 13 September 1995. There did not seem to be a regional pattern to exploitation or density trends in the purse seine fishery (Fig. 34). All high exploitation rates in the gillnet fishery occurred at the beginning and end of the season when densities were lowest (Fig. 35).

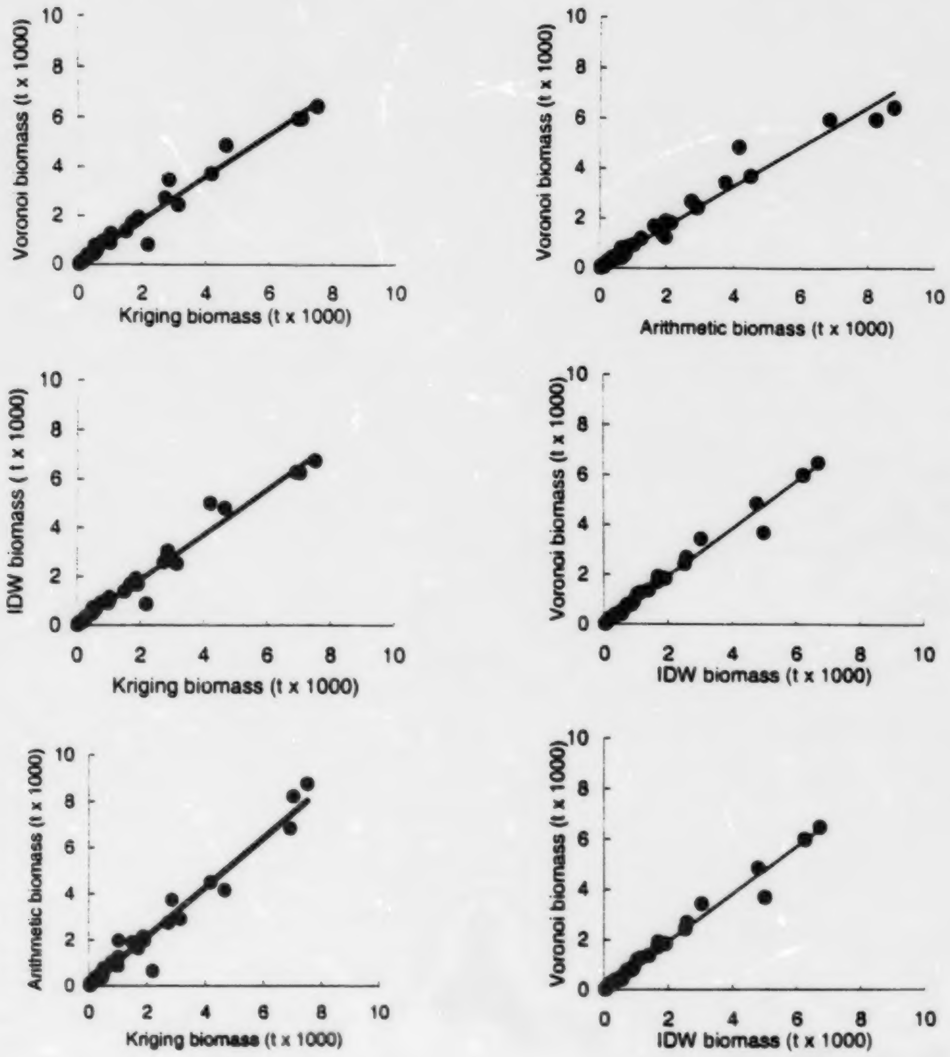


Fig. 28. Scatterplots and regression lines for comparison among estimation methods for gillnetter and purse seine data. Each point represents a night of either gillnet or purse seine data collection during regular fishing activity. IDW = inverse distance weighting; t, is metric tonnes.

Table 6. Sum of squared residual (SSR) values for stock assessment parameter regression models. Figure references are provided. Cat / Met is catch per metre searched, ER is exploitation rate.

Relationship	Model	SSR Gillnet Boat	All Gillnet Boats	Purse Seine Boat	Purse Seine Fleet
ln Density - CPUE	von Bertalanffy	8.4×10^5	8.2×10^5		
	Figure reference	Fig. 29	Fig. 29		
Density - Distance	Exponential	132		5.52	
	Reciprocal	125		5.48	
	Figure reference	Fig. 30		Fig. 30	
Density - Cat / Met	von Bertalanffy	0.23	4001	33	1090
	Linear	0.75	4009	31	1210
	Figure reference	Fig. 32	Fig. 32	Fig. 31	Fig. 31
Density - ER	Exponential		3.18		0.17
	Reciprocal		2.14		0.16
	Figure reference		Fig. 33		Fig. 33

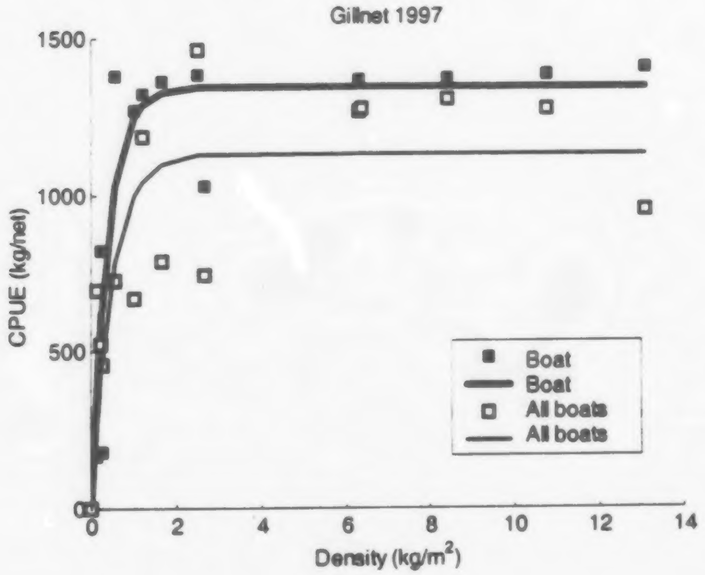


Fig. 29. Scatterplots and fit to von Bertalanffy model for relationship between gillnetter catch rates (CPUE kg/net) and density from boat collecting acoustic data and all boats in the Pictou, Nova Scotia gillnet fishery.

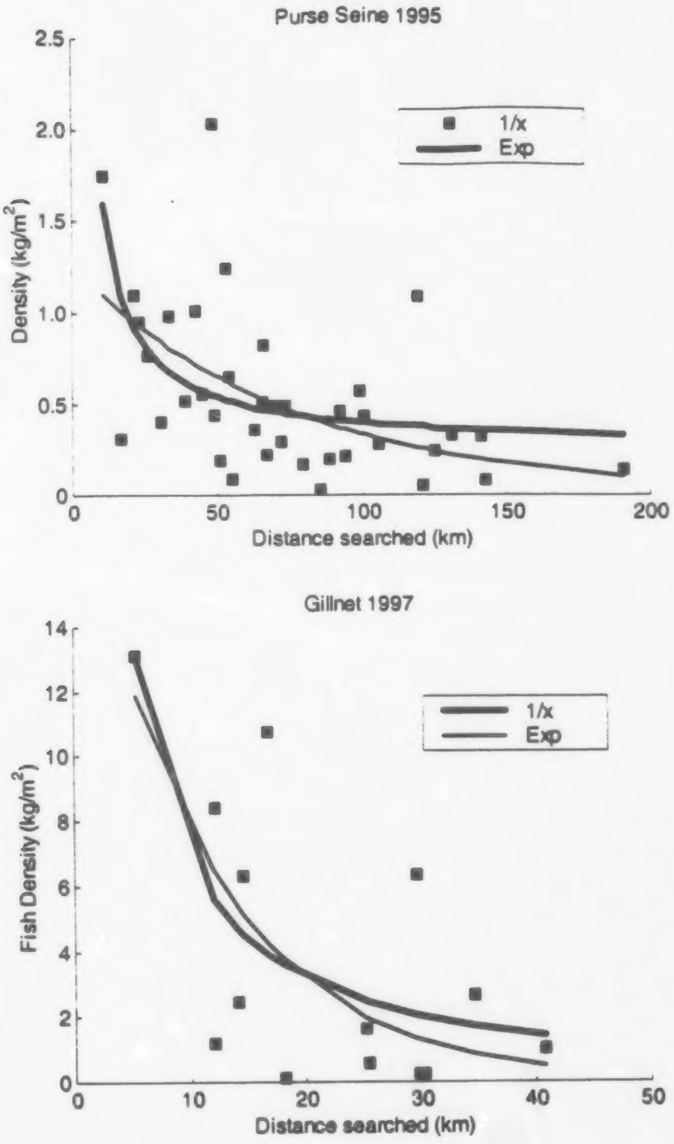
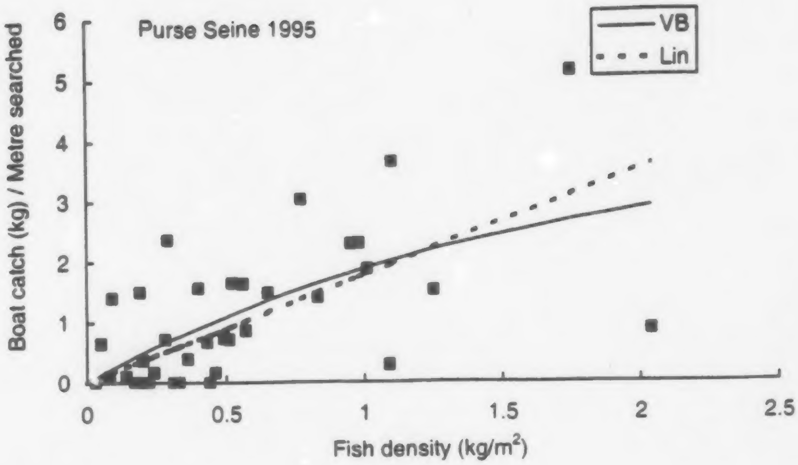


Fig. 30. Scatterplots and regression lines for relationship between fish density and distance searched for fish schools by boats collecting acoustic data. Chaleur Bay, purse seine (top), Pictou, Nova Scotia, gillnet (bottom). 1/x, reciprocal model; Exp, exponential model.



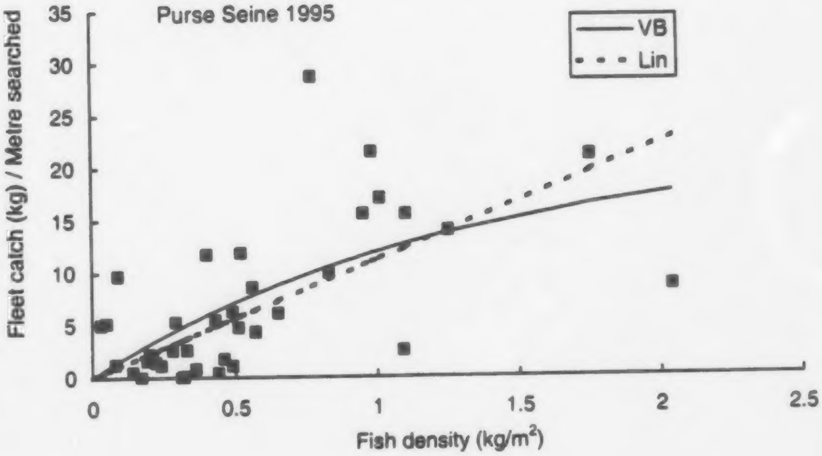
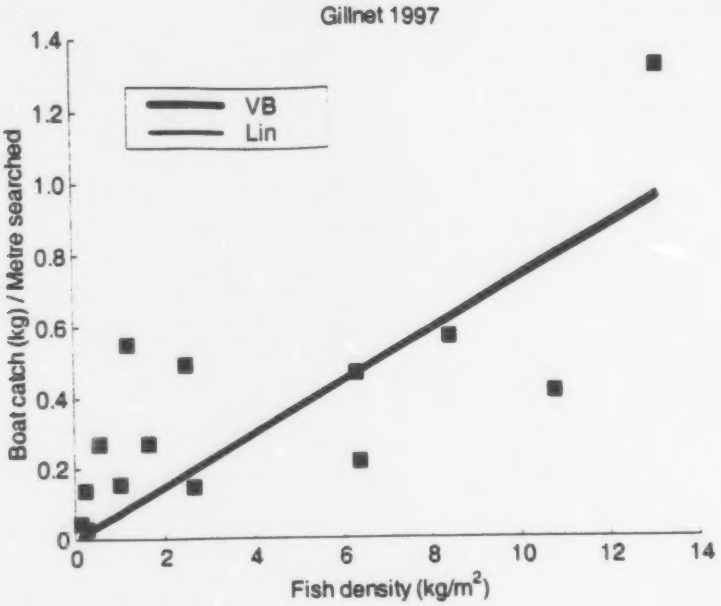


Fig. 31. Scatterplots and regression lines for relationship between catch rates (kg / metre searched) and fish density for Chaleur Bay, purse seine boat collecting acoustic data (top) and for all six boats in the purse seine fleet (bottom). VB, von Bertalanffy; Lin, Linear.



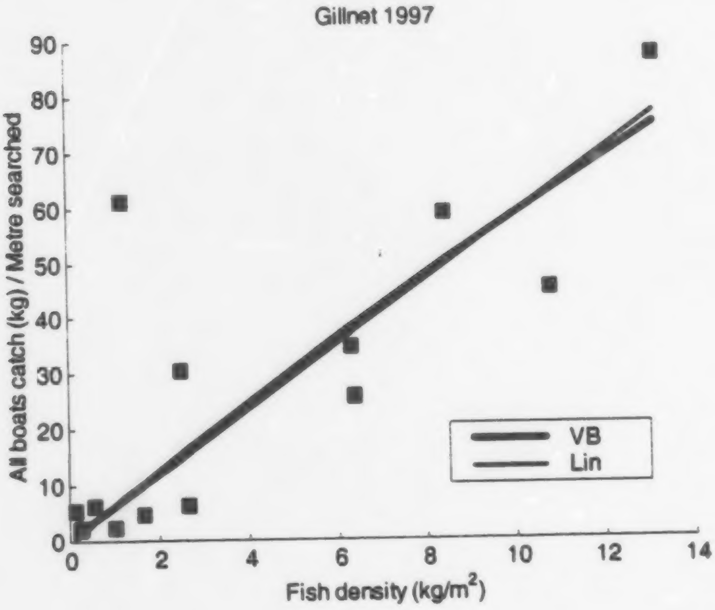


Fig. 32. Scatterplots and regression lines for relationship between catch rates (kg / metre searched) and fish density for Pictou, Nova Scotia, gillnet boat collecting acoustic data (top) and for All Boats in the Pictou gillnet fleet (bottom). VB, von Bertalanffy; Lin, Linear.

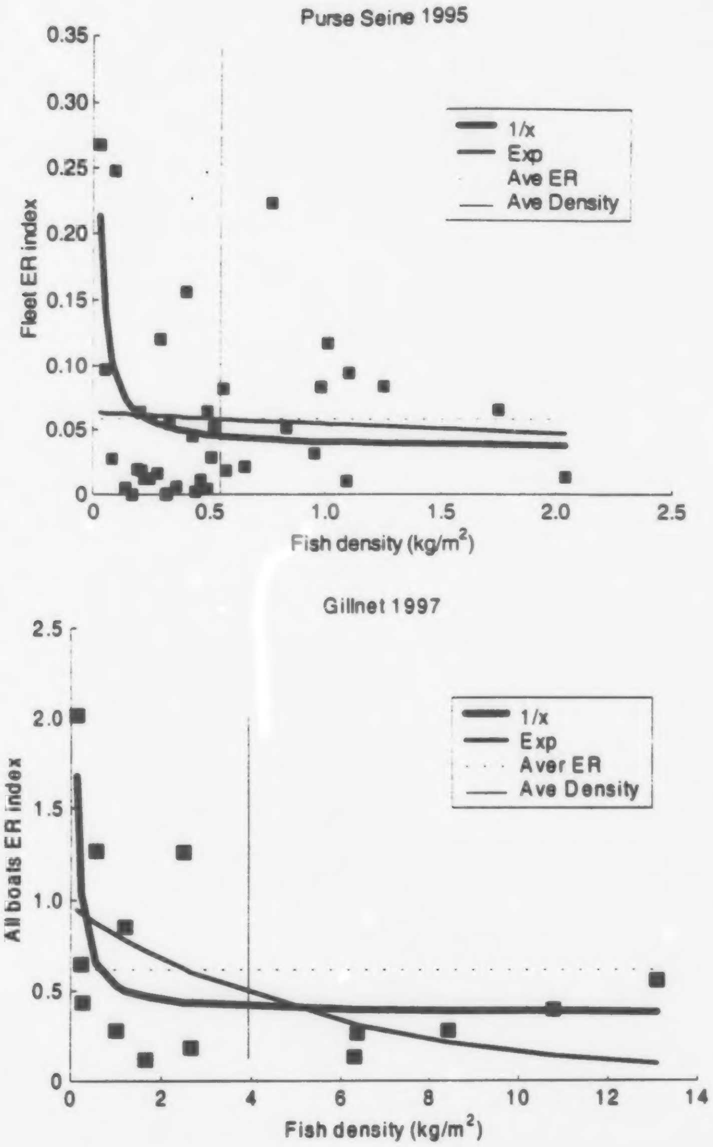
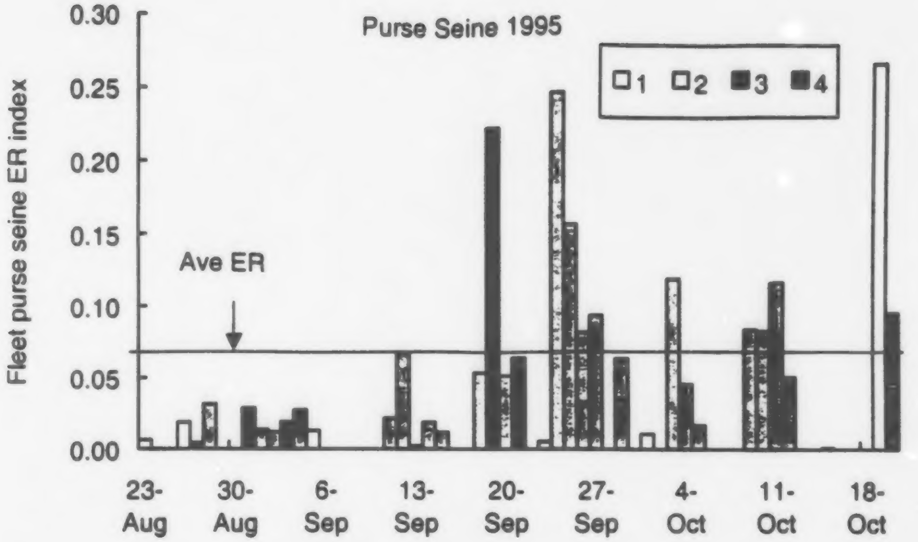


Fig. 33. Scatterplots and regression lines for relationship between exploitation rate index (ER) and fish density for All Boats in the Chaleur Bay, purse seine fleet (top) and All Boats in the Pictou, Nova Scotia, gillnet fleet (bottom). Average ER and fish densities are indicated by dotted lines. 1/x, reciprocal model; Exp, exponential model.



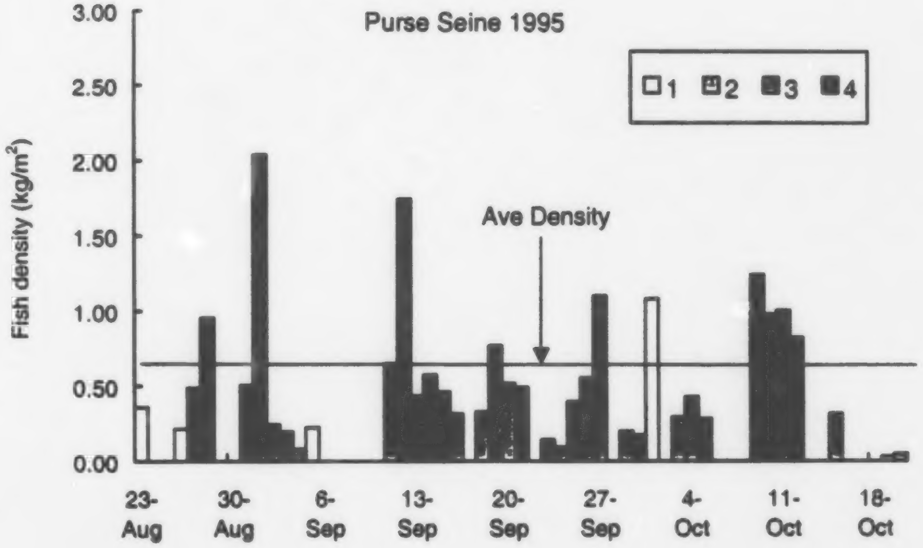
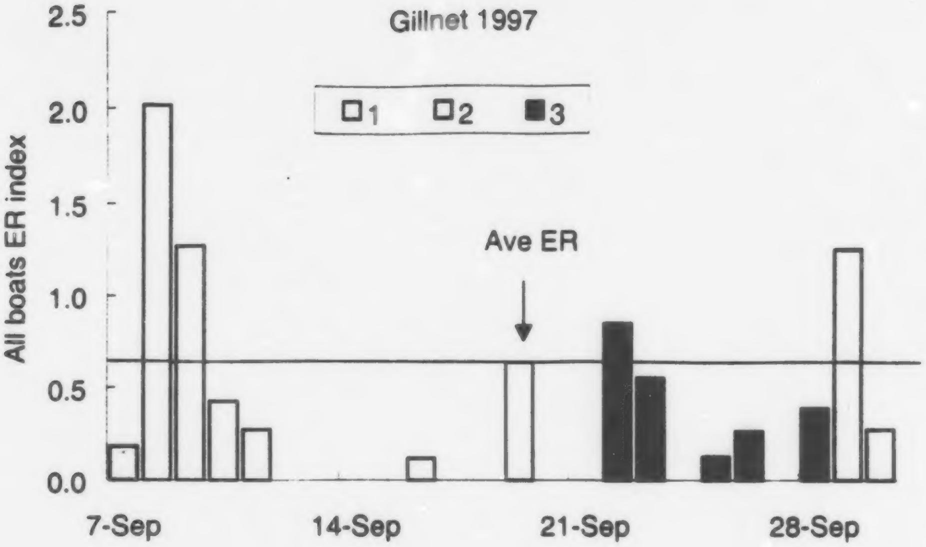


Fig. 34. Distribution over time by region of ER and fish density for Chaleur Bay, purse seiner collected data. Numbers refer to fishing regions defined in Fig. 19.



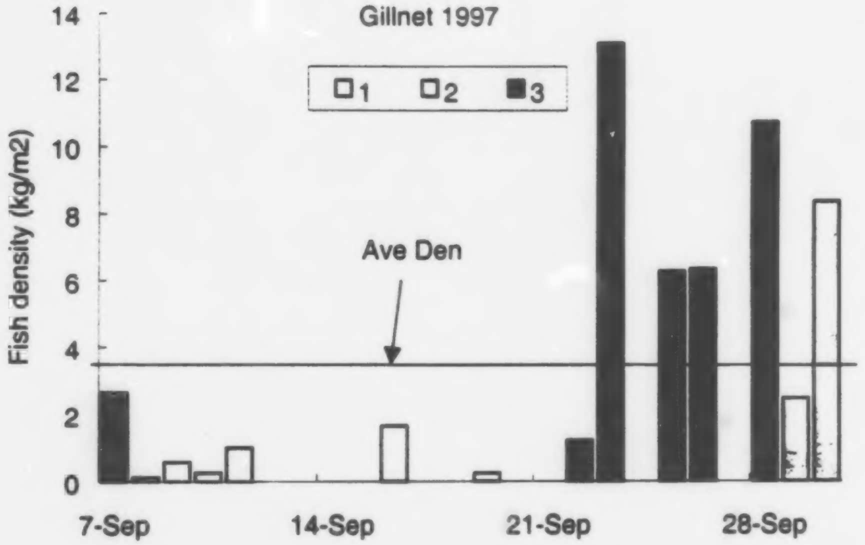


Fig. 35. Distribution over time by region of ER and fish density for Pictou, Nova Scotia, gillnetter collected data. Numbers refer to fishing regions defined in Fig. 18.

5.15 Discussion - Spatial and temporal trends

These analyses sought to determine the relative trends and relationships between density and key stock assessment parameters such as catch rates and exploitation rates. The high correlation among the estimation methods indicates that the choice of method used to estimate density will not affect conclusions regarding these relative relationships (Fig. 28). One reason for these high correlations among the methods is the low ratio of distance surveyed to survey area compared to other survey methods. For example, during acoustic surveys of the southern Gulf of St. Lawrence the maximum sampling rate does not exceed 0.50 km of transect surveyed per km^2 of survey area (Claytor and LeBlanc 1999). In this study, there was 2.4 km surveyed per km^2 of fishing area for the purse seine boat, and 55 km per km^2 of fishing area for the gillnet boat. This comparison of survey length is important because each 100m is a datum point. Transects for acoustic and trawl surveys in the southern Gulf of St. Lawrence are typically several kilometres apart (Claytor and LeBlanc 1998). This high sampling density, relative to other investigations, means that there is less interpolation among the points and the estimation method has relatively less effect on the results.

An important consideration in the selection of an estimation method is that it accounts for the clustering of data samples. Samples that are close together must have their influence reduced in the overall estimate because they do not represent as large an area as samples that are more distant from one another. The voronoi, kriging, and IDW methods accomplish this declustering. The arithmetic method, which is the unweighted average of all the points, does not take clustering effects into account and that is the reason why this method differs the most from each of the other methods (Isaaks and Srivastava 1989). For these data and for the purposes of this investigation, each of the above declustering methods would have sufficed and the voronoi method was chosen primarily for convenience of implementation.

The nightly limit imposed on each boat in the gillnet fishery is similar to the estimated asymptotic catch rate of 1353 kg/net for the gillnet boat model (Fig. 29). The boat collecting the acoustic data used 5 nets to fish each night. As a result, the 7000 kg nightly fishing limit would produce a catch rate of 1400 kg/net if this limit were caught each night. The asymptote was reached at a density of about 1 kg/m^2 while the densities observed during the fishing season ranged up to 10 kg/m^2 (Fig. 29). The asymptote for the entire fleet was lower than for the individual collecting the acoustic data but was still reached at about 1 kg/m^2 (Fig. 29). These results indicate there is little change in these catch rates over most of the densities observed during the fishing season and they would be of limited use in tracking daily abundance trends in this fishery. Many fisheries depend upon voluntary logbook programs to obtain these types of catch rate information and it is often the individuals with the highest interest and highest catch rates that participate in these programs. If fishing captains are able to consistently catch their nightly limits regardless of density, then relatively little information is being obtained from these programs for assessment of the stock. This affects the logbook program's usefulness for providing abundance indices for stock population models. On the other hand, a decline in logbook catch rates should serve as a major indicator of low densities and high exploitation rates in these types of fisheries. As a result, the effects of nightly limits whether because of boat capacity, management, or market quotas, must be considered in assessment model results.

Purse seine vessels have generally been thought not to provide useful catch rate information. It is generally thought that the efficiency with which purse seiners are able to find and catch schools of fish has meant that catches that result from them are not related to population numbers. For this fleet, the relationship between catch per set and density appears random. As a result, there is no catch rate data from the purse seine fishery that is comparable to kg/net from the gillnet fishery for this stock.

The inverse relationship between density and distance searched on the fishing grounds indicates that the amount of searching by purse seiners and gillnetters may provide a catch per unit of effort parameter that is indicative of population trends (Fig. 30). Purse seine and gillnet catch per metre searched for the boats collecting the acoustic data and for fleet catches indicate a relatively more linear relationship was observed using the catch / metre searched index than for the kg/net catch rate (compare Figs. 29, 31, 32).

The asymptotic relationship between the purse seine and gillnet exploitation rate indices and density implies there is a threshold density beyond which exploitation rate will drop slowly. The threshold may be a function of the boat limit and may be different if there were no nightly limits, but this hypothesis has not been tested. Nevertheless, exploitation rates that are considerably above average occur only at low densities for both types of fleets and it is these high exploitation rates that managers seek to avoid (Fig. 33). If there were a spatial or temporal trend to these high exploitation rates then a manager would have a tool for easily eliminating these from a fishery. For the purse seine fishery, above average exploitation rates occurred after 13 September but there is no obvious regional trend to explain the occurrence of the highest exploitation rates (Fig. 34). Additional analyses are needed to understand why these high exploitation rates occurred and if there is a preventative measure that could be applied.

For the gillnet fishery, the highest exploitation rates occurred at the beginning and end of the season (Fig. 35). This corresponds to generally low densities prior to 14 September and on 29 September. Managers may wish to consider limiting the season in this area. In 1997, the season was scheduled to open on 1 September in this area. The individuals fishing in the area voluntarily delayed their season because of low densities observed during acoustic surveys conducted during the first week of September. This delay no doubt had the effect of eliminating other high exploitation rates from this fishery during 1997.

A principal objective of this study has been to provide managers with a tool for identifying and eliminating high exploitation rates as a step in preventing overfishing. The combination of catch and acoustic data has identified high exploitation rates in each of the fisheries examined. In the gillnet fishery, there is a clear temporal pattern that managers could use to reduce the possibility of high exploitation rates in this fishery (Fig. 35). These high exploitation rates correspond to times of low density at the beginning and end of the season (Fig. 35). In the purse seine fishery, high exploitation rates were also identified and occurred in the latter half of the season but were mixed with average and below average exploitation rates. This mixture did not suggest any apparent temporal or regional trends that might be easily used to predict and eliminate the occurrence of high exploitation rates in this fishery (Fig. 34). In addition, there were no clear temporal or regional trends in density that would suggest that one time or place was more susceptible to high exploitation. Nevertheless, to be able to identify occurrences of high exploitation rates in this fishery is a major step forward in its management.

The ability to collect and analyze the acoustic data from regular fishing activity may not be possible for all laboratories to acquire. As a result, it was important to investigate whether the catch rates, kg/net, or catch/metre, would be useful indirect measures of the temporal trends in exploitation rates. For the purse seine analysis, there was no trend that could be used to identify high exploitation rates (Fig. 36). This result was expected because of the proportional relationship between density and catch/metre. For the gillnetters, catch/metre was a strong indicator of the high exploitation rates and low densities that occurred at the beginning of the season, although it would not have identified the high exploitation rate at the end of the season (compare Figs. 35, 36). Gillnet catch rates (kg/net) were below average at the beginning of the season, but there was little contrast between early and late season catch rates and they are unlikely to be a useful tool for managers to identify high in-season exploitation rates (Fig. 36).

Throughout this chapter interpretations of acoustic biomass estimates have been restricted to relative rather absolute estimates. Some of the factors that preclude an absolute biomass interpretation are: the variability of backscattering in high target concentrations, the relationship between target strength and fish size, vessel avoidance, and acoustic extinction from near surface reverberation (MacLennan and Simmonds 1992; Clay and Claytor 1998; Fréon and Misund 1999). The fisheries examined occur over a short period of time and on a single species in a particular phase of its life history, either as spawning or feeding aggregations. As a result, these estimates are likely to be relatively consistent and while it cannot be claimed that the absolute biomass of the schools estimated is known, relative changes are all that are required to identify spatial and temporal changes in exploitation rate in these fisheries.

The simultaneous occurrence of several herring fisheries in the southern Gulf of St. Lawrence makes it impractical, with current resources, to use these trends for making in-season adjustments in management plans. Thus, the identification of spatial and temporal trends in exploitation rates is viewed as becoming a part of the annual stock assessment process for southern Gulf of St. Lawrence herring. This process would be used to derive decision rules for governing the fishery during the coming season (Claytor 2000). The success of these rules in distributing exploitation rates, relative to the size of schools being fished, would be evaluated at the end of the season. This evaluation would subsequently form the basis for advising on changes in the decision rules. It is expected that the greatest potential for using these analyses for in-season management occur where a single fleet sequentially harvests a series of stock components in time and space.

Collecting acoustic data and information on searching effort has several advantages over more traditional forms of data collection for fisheries stock assessments. They provide marked improvement over kg/net indices, particularly when there are daily or trip limits on catches resulting from regulatory, market, boat capacity, or environmental sources. These techniques apply to a wide variety of fisheries where the species of interest is detectable by acoustic methods either as schools or individuals and are particularly suitable for single species pelagic fisheries.

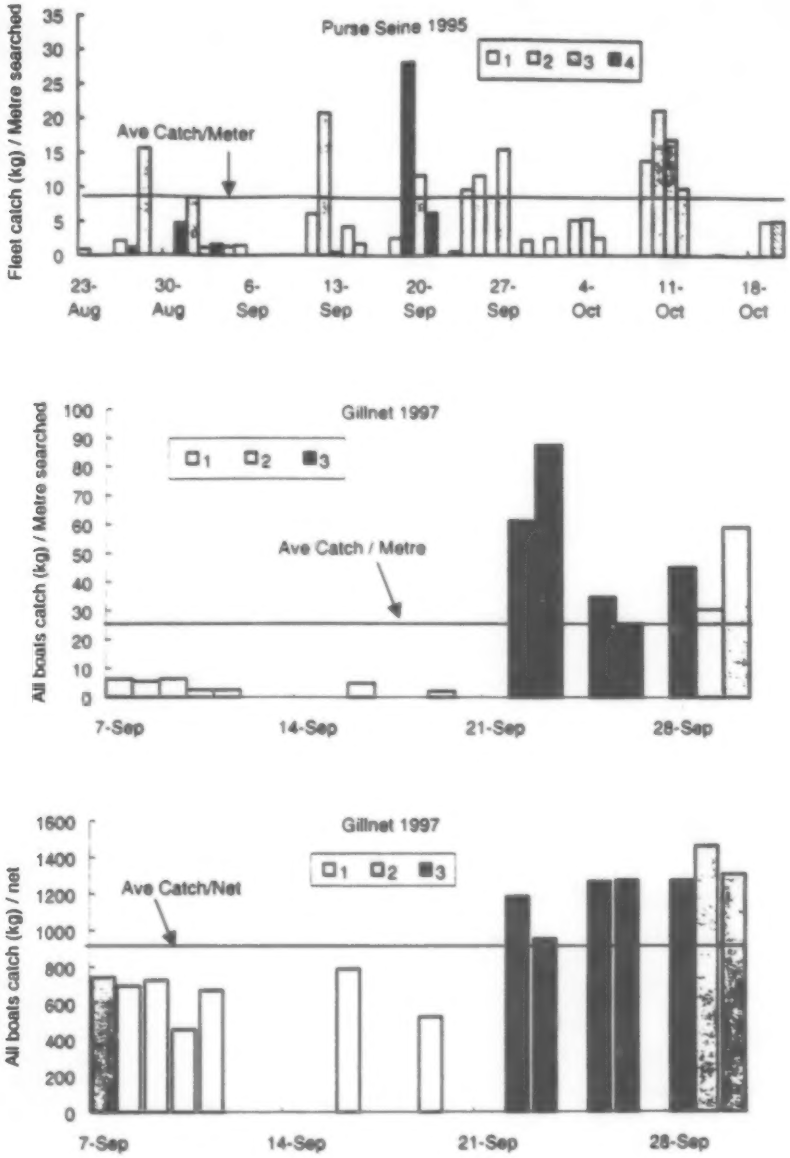


Fig. 36. Distribution over time by region of catch/metre for the Chaleur Bay, purse seine fleet and catch/metre and catch/net (CPUE kg/net) for all Pictou, Nova Scotia, gillnetter boats. Numbers refer to fishing regions defined in Figs.18,19.

6. Simulation to test the analytical method

6.1 Introduction

The analysis of acoustic data collected during regular fishing activity (Chapter 5) and the review of the factors affecting abundance indices (Chapter 2) raises three important questions with respect to determining whether or not the estimates from these data are abundance indices. How does the movement of fish during the searching activity affect the estimate? How does the distribution of the fish affect the estimate? How does fishing and depleting the resource during the searching activity affect the estimate? A simulation model approach has been used to answer these questions. This model is restricted to conditions that are compatible with the inshore gillnet herring fishery in the southern Gulf of St. Lawrence. The reason for this restriction is that the scale is smaller and the model more easily developed than one that would be compatible with the purse seine fishery. A simulation compatible with the purse seine fishery would provide a test for the effect of scale in interpreting the results.

The model simulates a local spawning herring aggregation and a gillnet fishery. One boat is simulated to collect the type of acoustic data obtained during the gillnet fishery. It searches for fish schools and fishes following a simple set of searching and fishing rules. Fishing locations for the remainder of the fleet were selected in a manner that was consistent with captains being able to locate higher than average densities for fishing. A simple probability model using the cumulative distribution of densities was used to determine these locations (Appendix 2). Four conditions of fish movement and fishing fleet activity are examined. These are fishing and movement of the fish school, fishing with no school movement, no fishing but with school movement, and no fishing and no school movement. Five fish distribution types are examined. These are: a single spike (spiky), average, flat, and intermediate between spiky and average (IAS), and intermediate between average and flat (IAF). These are subsequently quantified using the percentage of the area that contains the mid 75% of the biomass. Each night of the simulated fishery consisted of four hours of simulated data collection, searching, and fishing. Six indices of biomass trends were examined from the simulated data collected during each night. Three of these were derived from searching activity: searching for schools for the entire four hours using spatial statistics to estimate biomass (Searching - Total), searching for schools for the entire four hours but using the arithmetic average of the simulated data points (Arithmetic), and, searching for fish but using only the simulated data collected up to the time that the boat limit was caught (Searching - Fishing). Three indices were derived from simulated survey techniques: random tows, random transects, and systematic transects.

It is not claimed that the model is an exact replicate of fish movement and fishing captains' behavior. The objective is to create a variety of models compatible with what is known from the literature and experience and to study the properties of various stock indices under these assumptions. The rationale of this approach is that a good index should be proportional throughout the range of fish and fishing captain's behavior that is plausible according to current knowledge and experience.

6.2 Gillnet fishery simulated data

The data collection and acoustic calibration methods have been previously described in Chapter 5. The approach consists of installing a scientific sounder and a transducer on board a gillnet vessel, that are separate from the sounder and transducer gillnetters normally use during their fishing activity. The sounder is connected to an on-board computer that digitally records all the sounder information directly to computer files. The captain turns the unit on when the vessel leaves port and it is turned off when the vessel returns to port. There is continuous data collection during the searching and fishing sets for each night of fishing.

The sounder information along the fishing track is divided into 100m increments and a datum point is the average density and geographic position along the increment. A density of 0.0625 kg/m2 is consistent with the beginning of search activity (Figs. 23, 24).

Plots of density over time in the gillnet fishery search area indicate the range of densities encountered on the fishing grounds through the night (Fig. 37). For some of these periods of

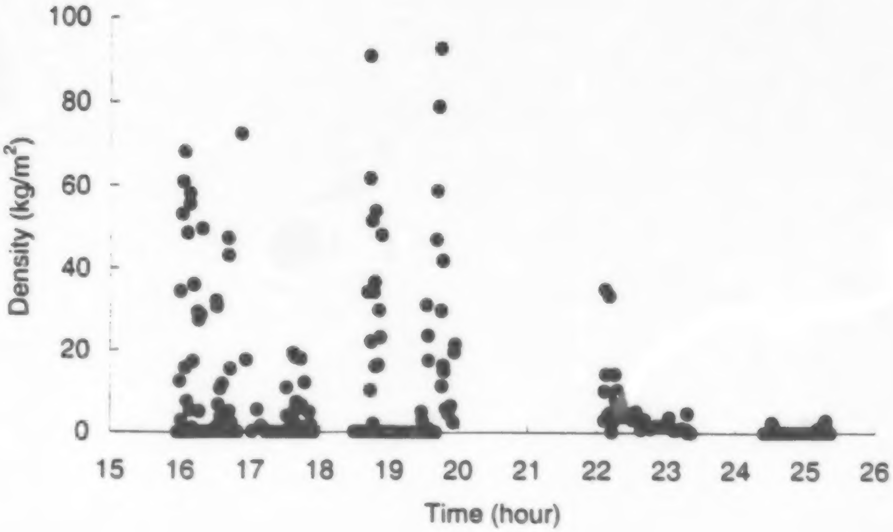
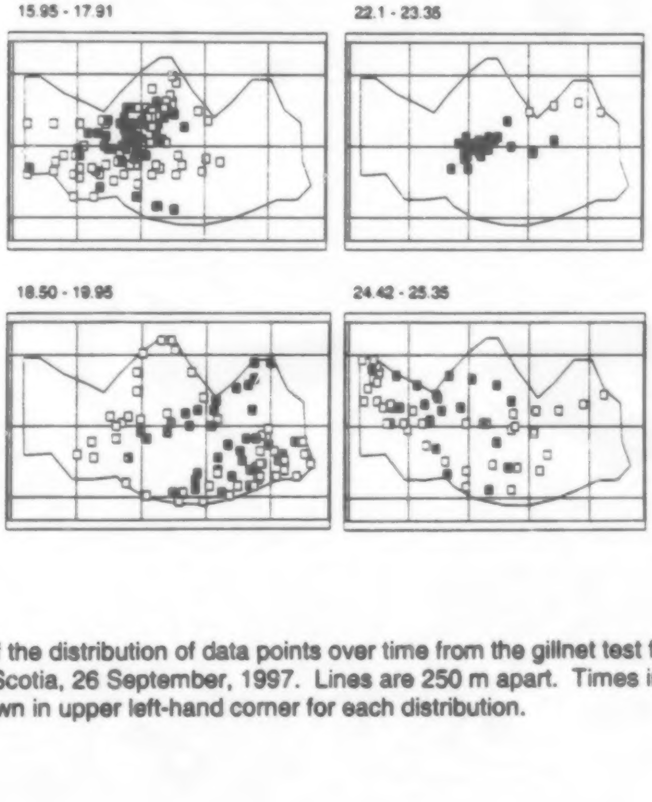


Fig. 37. Distribution of acoustic density encountered over time by gillnet test fishing boat, Pictou, Nova Scotia, 26 September, 1997. Missing data occurs while the net is set.


15.95 - 17.91

22.1 - 23.36

18.50 - 19.95

24.42 - 25.35

Fig. 38. An example of the distribution of data points over time from the gillnet test fishery boat, Pictou, Nova Scotia, 26 September, 1997. Lines are 250 m apart. Times in decimal hours are shown in upper left-hand corner for each distribution.

time, the boat was searching in different parts of the search area, in other cases a period of 6 or more hours passed between searches in overlapping areas (Fig. 38). As a result, investigating the effects of movement and time on the index derivation is important.

The 1997 Pictou gillnet fishery was used as the template for the simulation model. The boat collecting the simulated data, with the acoustic equipment on board, is designated the acoustic boat. This boat, as well as all other boats in the simulated fleet, was subject to a nightly boat or catch limit of 7500 kg. This regulation had the effect of restricting catches even when densities were high and its effect was examined in the simulation. The average number of nets used per gillnetter per night in this simulated fishery was five. Simulated catch rates (CPUE) were calculated as the catch divided by nets (kg/net) for the acoustic boat and all fleet boats.

In this study, the simulation model is restricted to conditions that are compatible with the fishery and fish characteristics for the inshore gillnet fishery on spawning aggregations. However, similar questions arise from the analysis of the purse seine fishery data (Claytor and Clay 2001). The major differences between these two fisheries are that the purse seine fishery searching and fishing on each night occur over a much broader area, and the fish are in large feeding or pre-migrating shoals and not in small, dense spawning aggregations (Figs. 18, 19, 23, 24). These differences emphasize the importance of examining characteristics compatible with the purse seine fishery in a future investigation.

6. 3 Simulation model - Description

The simulation model tested three biomass indices derived using simulated data collected by a fishing boat while it searched for schools of fish, and three indices derived from survey techniques. The simulated searching indices were Searching - Total, where the index was based on simulated data collected throughout the simulated fishing trip, Searching - Fishing, where the index was based on simulated data collected only up until the time that the boat limit was caught. These two indices used voronoi polygons to derive area weighted biomass indices. The third index from the searching simulated data was simply the arithmetic average of the Searching - Total simulated data points and was designated as Arithmetic. The three survey indices were derived from a simulated random tow survey, a simulated random transect survey, and a simulated systematic transect survey. In total six indices were compared against the known simulated biomass.

These indices were tested against five simulated distribution types ranging from a single spike to a uniform flat distribution. For each simulated distribution type, a range of 16 simulated stock sizes was examined. For each combination of simulated stock size and distribution, four simulated fish movement and fishing conditions were examined. These were: fish school movement and fishing, no fish school movement and fishing, fish school movement and no fishing, and no fish school movement and no fishing.

Details of the elements of the simulation are provided in Appendix 2. An overview of the simulation elements is provided below.

6.4 Simulated searching area and distribution of fish

The simulated search area was scaled to a 700 x 700 metre square. This was equivalent to the average area searched each night in the Pictou, Nova Scotia gillnet fishery (Tables 7, 8). A three dimensional representation of the data for each of the searching areas for each night of fishing illustrates the variation in fish distributions occurring in this fishery (Fig. 39).

The simulated fish schools to be searched consisted of one to ten clusters. Each cluster is defined by a bi-normal density function with the cluster centre defined by x-y coordinates and with a cluster covariance matrix equal to a multiple of the identity matrix. Thus, the clusters were radially symmetric about their centres. The number of clusters and their standard deviations varied depending on the type of distribution to be created. Five types of distributions were examined and ranged from a spiky distribution consisting of a single cluster with a small standard deviation to a flat distribution with one cluster with a very large standard deviation (Fig. 40; Appendix 2). Each of these types of distributions, except the flat distribution, were observed in the gillnet data collected in the 1997 Pictou fishery (Figs. 39, 41).

The cluster centres were restricted to a smaller 500 x 500 metre square within the search area (Fig. 42). The reason for this restriction was to ensure that the majority of the distribution would be within the sampling area and that in the average distribution (Appendix 2) the edge of the search area would coincide with the 0.0625 kg/m2 contour as is the case with the Pictou fishery data (Fig. 43). The biomass in each of the clusters was scaled so that the total biomass in the search area would be one of 16 pre-selected values ranging from 50 to 15,000 tonnes (Appendix 2). This range included simulated biomass values that were smaller and larger than those observed in the real data (Table 7). The true simulated stock size was determined at the beginning of the simulation using numerical integration (Appendix 2).

The location of the centres was determined by selecting x-y coordinates from a uniform random distribution. Intermediate distributions between spiky and average and average and flat were formed by forcing the centres to remain a certain number of standard deviations apart (Appendix 2). The distribution types were described quantitatively using the percentage of the search area that contained 75% of the biomass, similar to the method used by Swain and Sinclair (1994) and Swain and Morin (1996) (Appendix 2).

The simulation was set up with a clock and the total time provided for simulated data collection was scaled to 4 hours, which is similar to the average amount of time spent collecting data in the Pictou fishery (Table 7). Events such as movement of the fishing boat, fishing, and movement of survey boats were set to occur at predetermined time intervals. The basic clock tic or time interval was scaled to 0.015 hours and was derived by determining the amount of time required to collect the average number of data points (224) in the average time spent searching (4.26 hours) in the real data (Table 7).

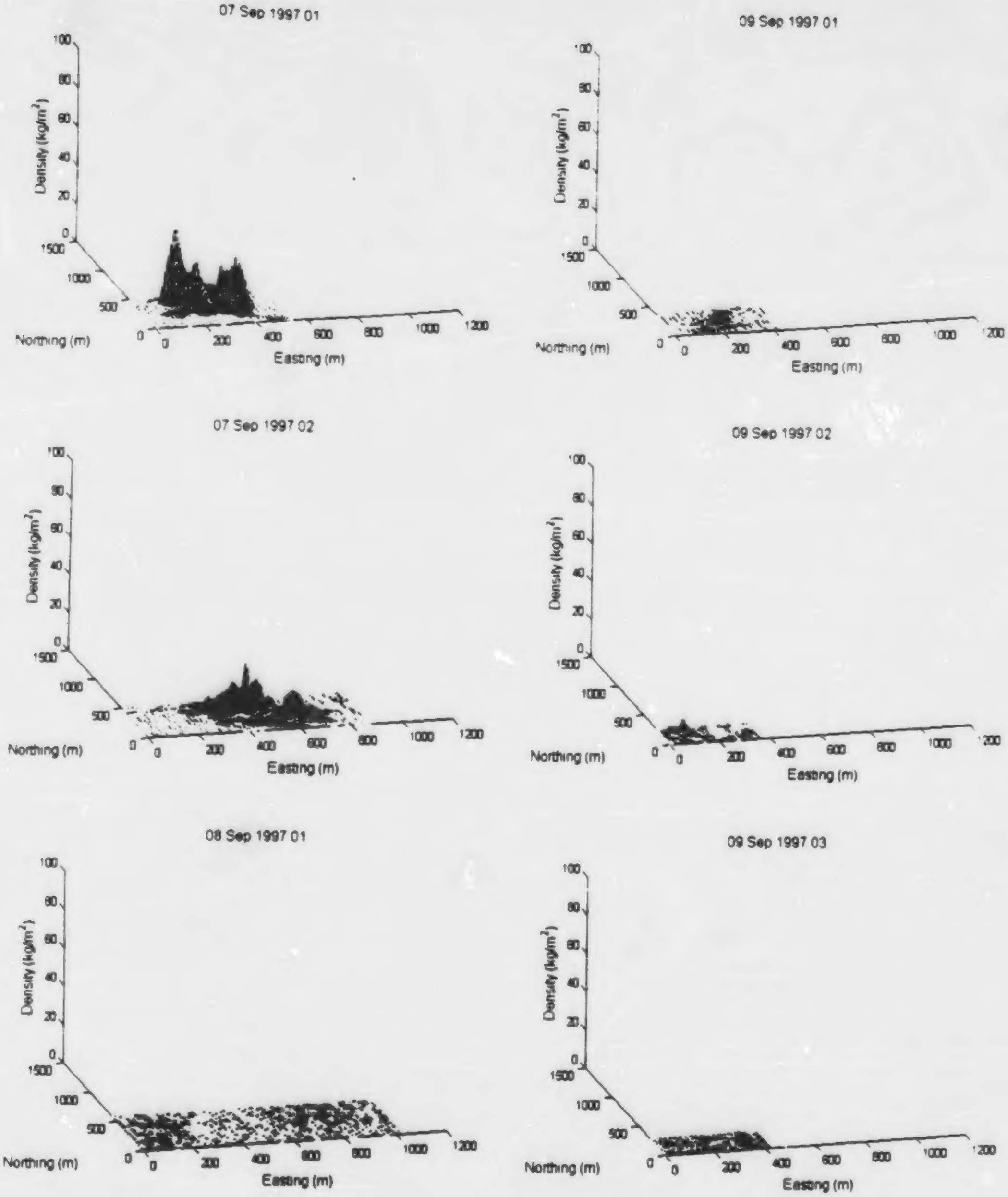
F2

Table 7. Summary data for 1997 Pictou, Nova Scotia herring inshore gillnet fishery. t is metric tonnes.

Date	Observations	Area (m^2)	Distance (m)	Hours	Biomass (t)	Density (kg/m^2)
907	351	451600	34652	7.20	1196	2.65
908	182	430300	18095	2.76	50	0.12
909	260	223494	25423	5.10	126	0.56
910	304	695137	30259	4.93	175	0.25
911	416	363021	40716	10.81	365	1.01
916	255	622252	25212	4.97	1022	1.64
919	301	402656	29846	3.80	98	0.24
922	126	710300	12017	2.36	863	1.21
923	55	63369	5297	1.62	831	13.11
925	149	623251	14598	2.17	3931	6.31
926	305	449448	29716	5.38	2866	6.38
928	176	179607	16776	3.79	1934	10.77
929	143	138507	14129	2.86	343	2.48
930	123	307178	12098	1.83	2583	8.41
Average	225	404294	22060	4.26	1170	3.94
Minimum	55	63369	5297	1.62	50	0.12
Maximum	416	710300	40716	10.81	3931	13.11

Table 8. Fishery data for 1997 Pictou, Nova Scotia herring inshore gillnet fishery.

Date	Acoustic Boat Catch	Fleet Catch	Number of Gillnetters	No. Nets	Acoustic Boat CUE	Fleet CUE
907	5144	218943	59	295	1029	742
908	827	100704	29	145	165	695
909	6904	159896	44	220	1381	727
910	907	75170	33	165	181	456
911	6348	100566	30	150	1270	670
916	6824	122290	31	155	1365	789
919	4115	62958	24	120	823	525
922	6618	736133	124	620	1324	1187
923	7058	463635	97	485	1412	956
925	6854	508077	80	400	1371	1270
926	6428	766805	120	600	1286	1278
928	6950	761208	119	595	1390	1279
929	6935	432364	59	295	1387	1466
930	6887	714589	109	545	1377	1311
Average	5629	373096	68	342	1126	954
Minimum	827	62958	24	120	165	456
Maximum	7058	766805	124	620	1412	1466



07 Sep 1997 01

09 Sep 1997 01

07 Sep 1997 02

09 Sep 1997 02

08 Sep 1997 01

09 Sep 1997 03

Fig. 39. Three dimensional representation of herring densities estimated from gillnet test fishery boat, Pictou, Nova Scotia, September 1997. Title of each figure gives day, month, and sequential number of searching area examined for each night of fishing.

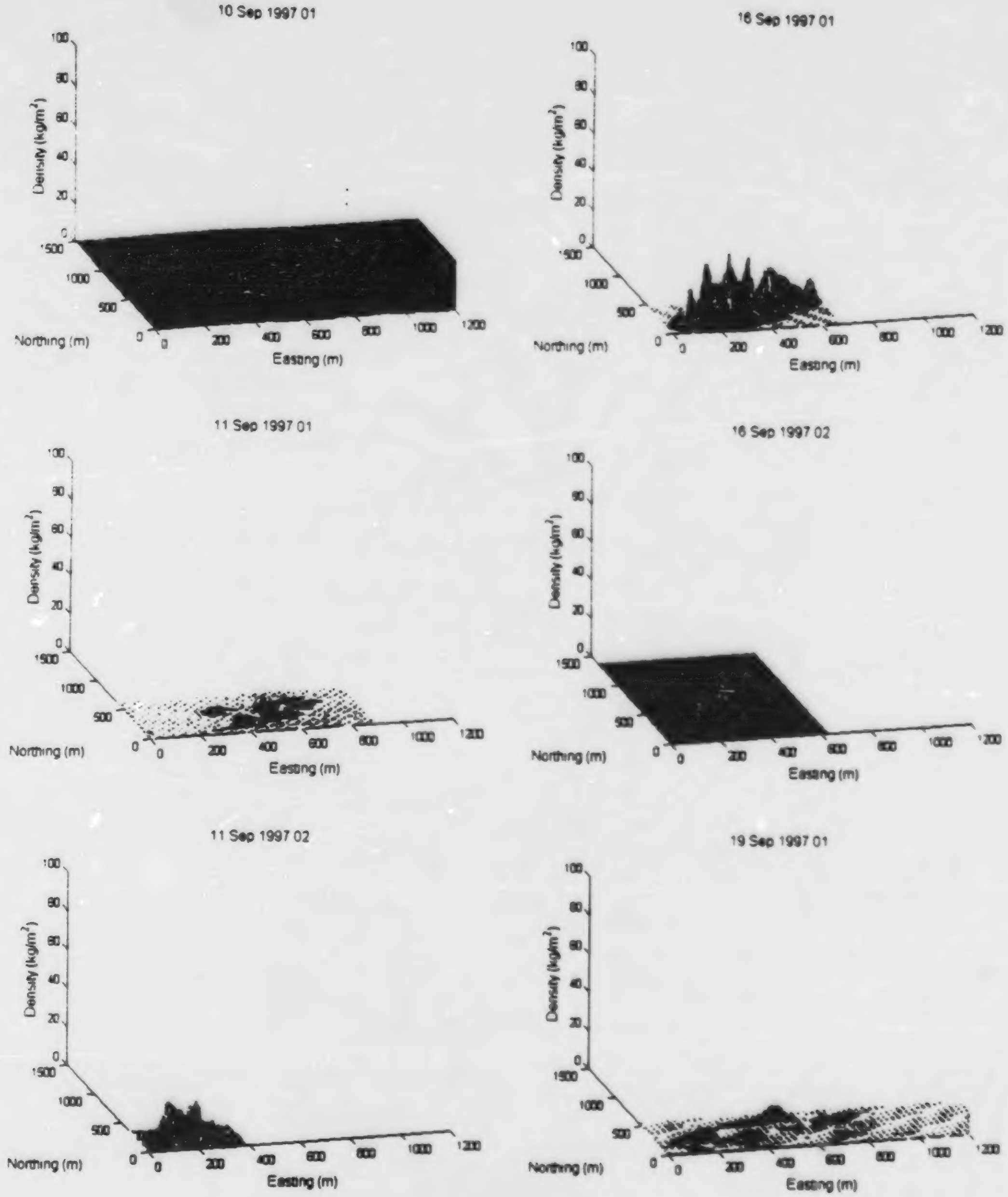

10 Sep 1997 01
16 Sep 1997 01
11 Sep 1997 01
16 Sep 1997 02
11 Sep 1997 02
19 Sep 1997 01
Density (kg/m²)
0
20
40
60
80
100
Northing (m)
0
500
1000
1500
Easting (m)
0
200
400
600
800
1000
1200

Fig. 39. (cont.)

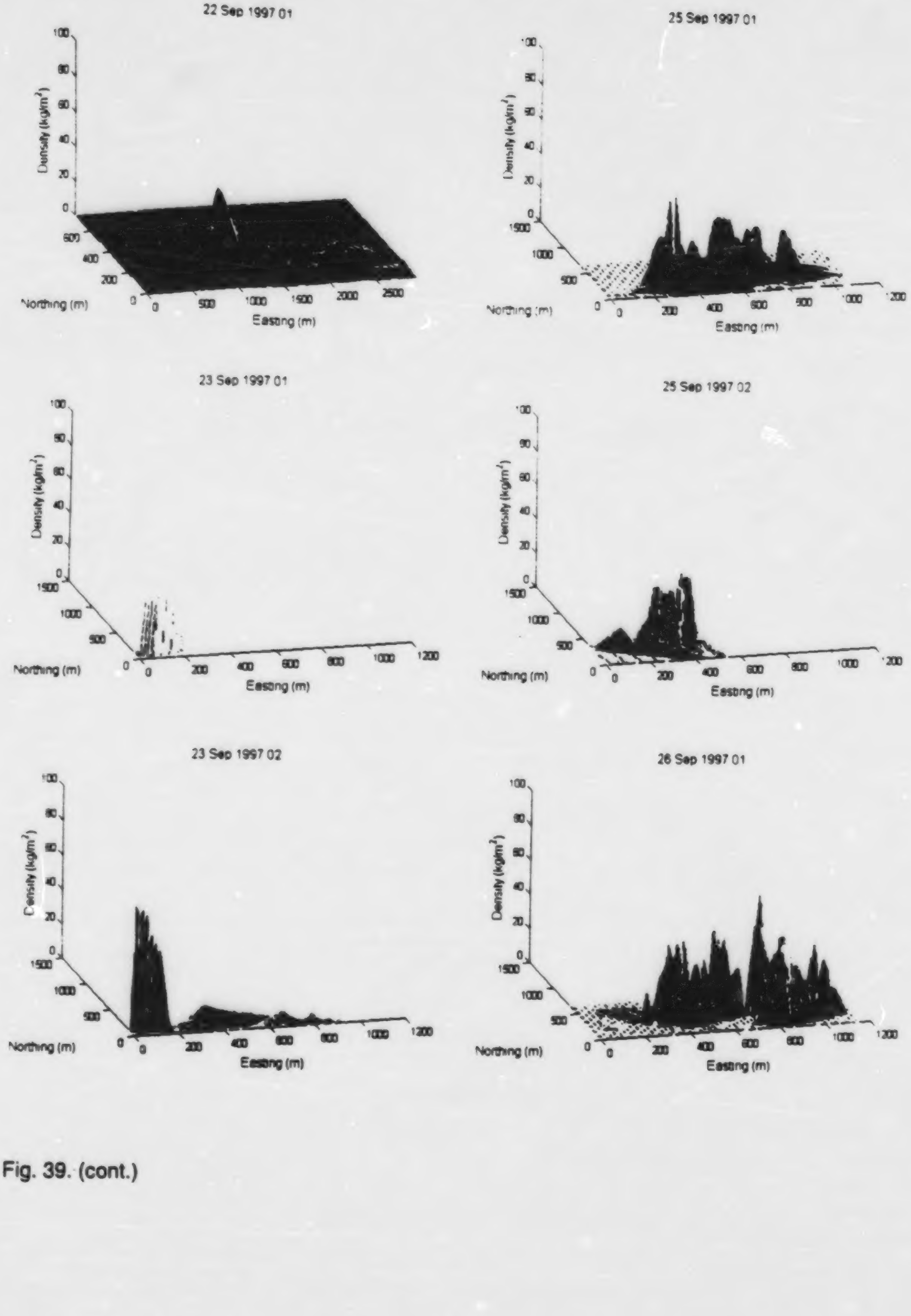
22 Sep 1997 01
Density (kg/m²)
100
80
60
40
20
0
Northing (m)
600
400
200
0
Easting (m)
0
500
1000
1500
2000
2500
25 Sep 1997 01
Density (kg/m²)
Northing (m)
1500
1000
500
0
Easting (m)
0
200
400
600
800
1000
1200
23 Sep 1997 01
Density (kg/m²)
Northing (m)
Easting (m)
25 Sep 1997 02
Density (kg/m²)
Northing (m)
Easting (m)
23 Sep 1997 02
Density (kg/m²)
Northing (m)
Easting (m)
26 Sep 1997 01
Density (kg/m²)
Northing (m)
Easting (m)

Fig. 39. (cont.)

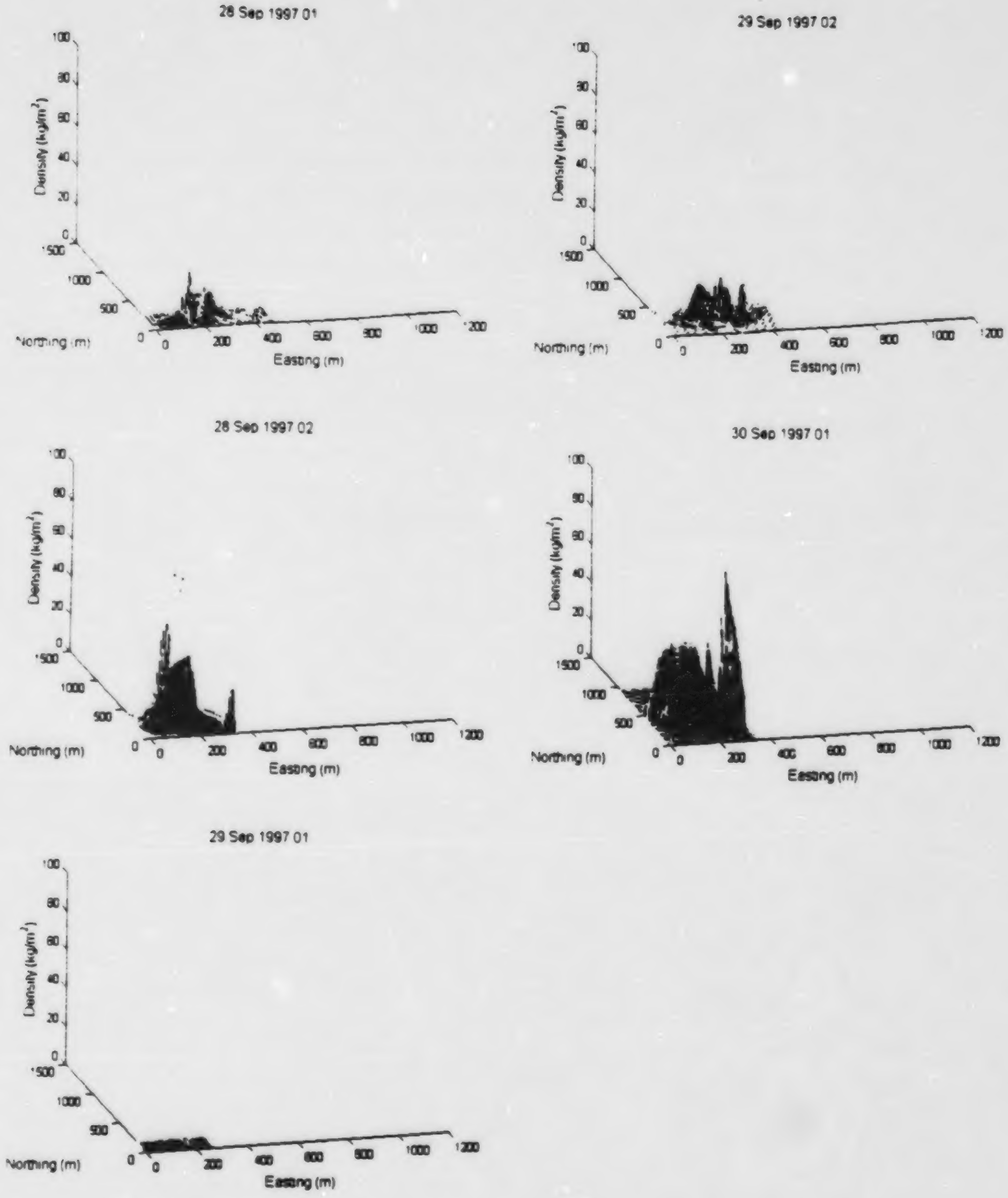

28 Sep 1997 01
29 Sep 1997 02
28 Sep 1997 02
30 Sep 1997 01
29 Sep 1997 01
Density (kg/m^2)
0
20
40
60
80
100
Northing (m)
0
500
1000
1500
Easting (m)
0
200
400
600
800
1000
1200

Fig. 39. (cont.)

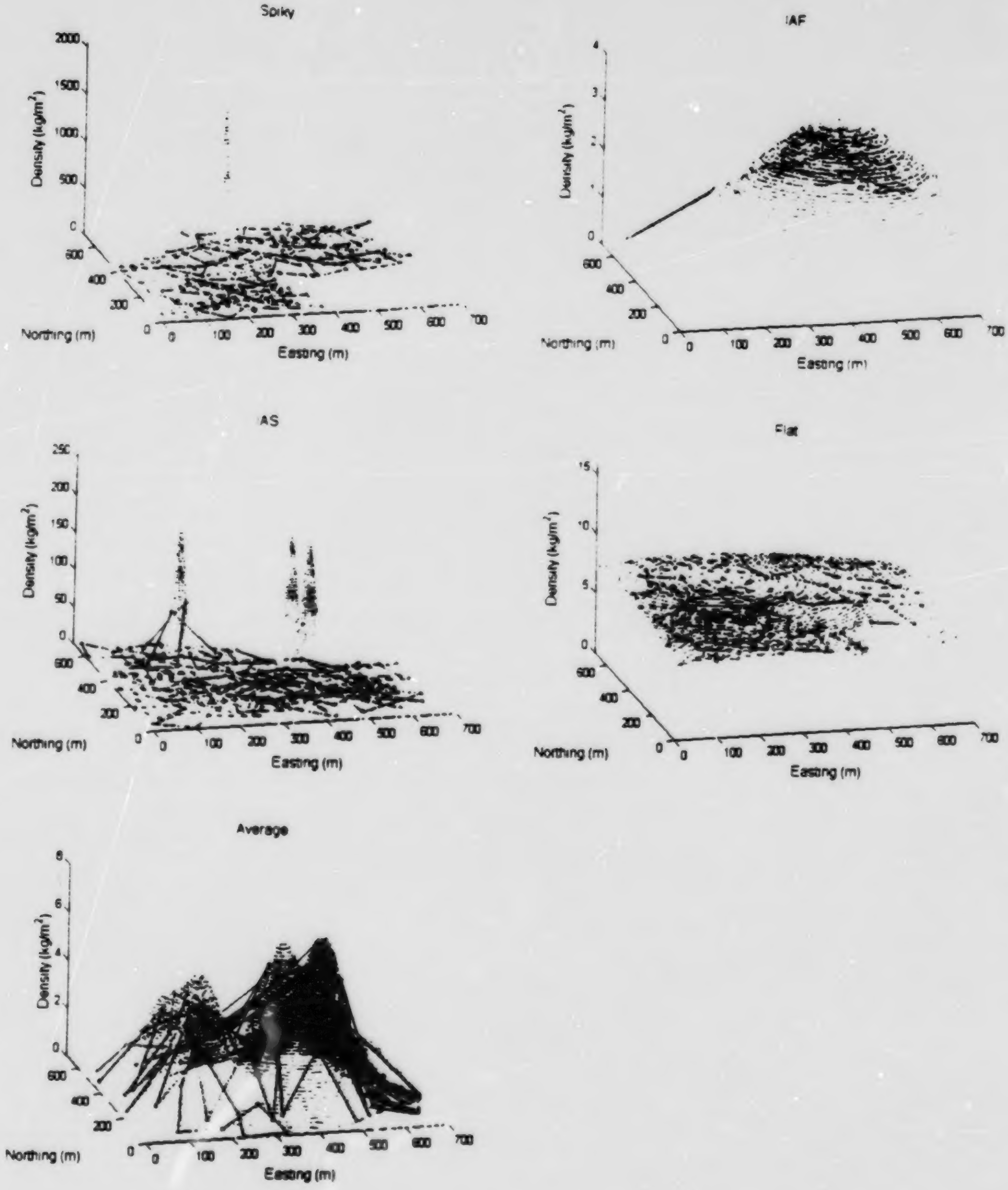
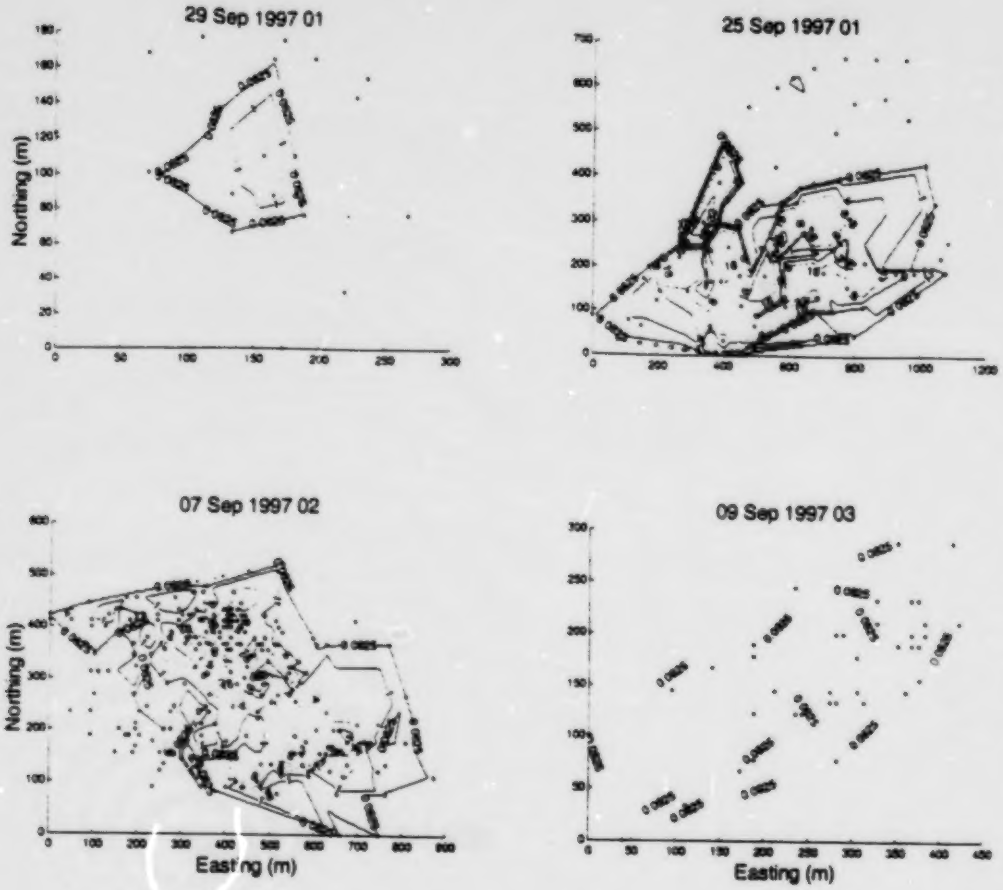


Fig. 40. Sample of distributions tested in simulation. Black lines show the fishing track of the gillnet test fishing boat as it collected acoustic simulated data.


29 Sep 1997 01

25 Sep 1997 01

07 Sep 1997 02

09 Sep 1997 03

Fig. 43. Examples of distributions from gillnet test fishing boat collecting acoustic data during the Pictou, Nova Scotia, 1997 gillnet fishery. Contour lines are in kg/m^2. Closed circles are sample points every 100m.

6.5 Simulated fish movement

Fish movement was simulated by moving the cluster centres up to 200 metres every five minutes of simulated time. The five minute time interval for movement was arbitrary and was chosen to save computing time. The alternative would have been to move the school centres a smaller distance at each 0.015 time step which would have greatly increased the computing time.

The speed and time intervals were chosen to represent realistic movement of herring in the area and as a compromise between computing time and realism. Herring schools have been found to migrate on average at about two-thirds a body length per second (Hafsteinsson and Misund 1995). The average body length of southern Gulf of St. Lawrence herring is about 0.30 metres (Claytor et al. 1998b). Moving 200m every five minutes would correspond to about 0.67 m / sec or about two body lengths per second. This speed should present a good test of the method with respect to fish movement. The distance and direction were chosen from uniform random distributions (Appendix 2). Often herring schools have been found to move in response to tidal changes, but these are usually observed over larger areas than the one examined here (Fréon and Misund 1999). In this simulation, movement direction was chosen at random because of the relatively small scale of the investigation and because fishing on schools usually occurs during slack tides in this fishery. As a result, tidal influences would be minimal and movement would tend to be more at random in response to fishing vessels rather than tide. If the distance or direction to be moved, placed the cluster centre outside of the central 500 x 500 metre area, then additional distance and direction choices were made until this condition was satisfied. Examples of cluster movement in the spiky and average situation indicate that cluster centres moved from one side of the search area to the other during the four hour period (Figs. 44, 45).

6.6 Simulated data collection

All biomass index simulated data, from fishing and surveys, were collected simultaneously during each simulation (Figs. 46-50).

6.7 Simulated survey data

Random tow locations were selected within the search area using a uniform random distribution. The number of random tows was determined by dividing the total time for the night (4 hours) by the time interval allocated to each random tow (30 minutes). For this simulation, the number of tows per night was 9, because one tow was made at the beginning of the simulation time clock and one at the end (Figs. 46 - 50). The length of each tow was 200 metres and tows were made in a random direction from each starting point. Tow locations were ordered by distance from the origin to determine the sampling sequence. If the end of the tow was outside the search area then a new direction was selected until the condition that the tow end in the search area was met. Average density along the tow was estimated using numerical integration (Appendix 2). Starting points for random transects were selected along the y axis for each simulation using a uniform random distribution and were ordered by distance from the origin. The number of transects chosen was based on the total time (4 hours) divided by the time between transect starts, 30 minutes. This meant that a total of 8 complete transects could be done in the 4 hours of the simulated time (Figs. 46-50). Simulated data along the transect were estimated in 100 m increments by numerical integration (Appendix 2).

Systematic transects were selected so that there was equal spacing between the transects. The number of transects was determined in the same manner as for random transects, and the simulated data were collected in 100 metre increments by numerical integration (Appendix 2).

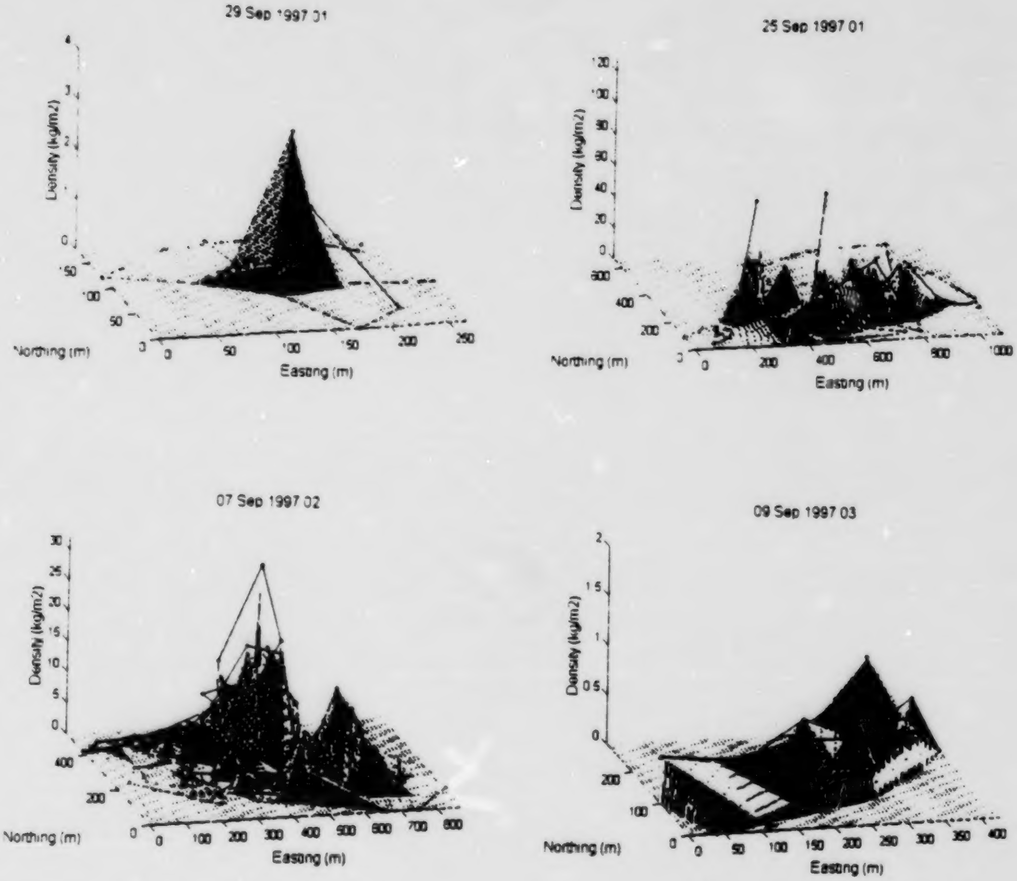


Fig. 41. Examples of distributions from gillnet test fishing boat collecting acoustic data during the Pictou, Nova Scotia, 1997 gillnet fishery. Black lines show search track of boat during the indicated night of fishing. These actual distributions are comparable to simulated distributions in Fig. 40.

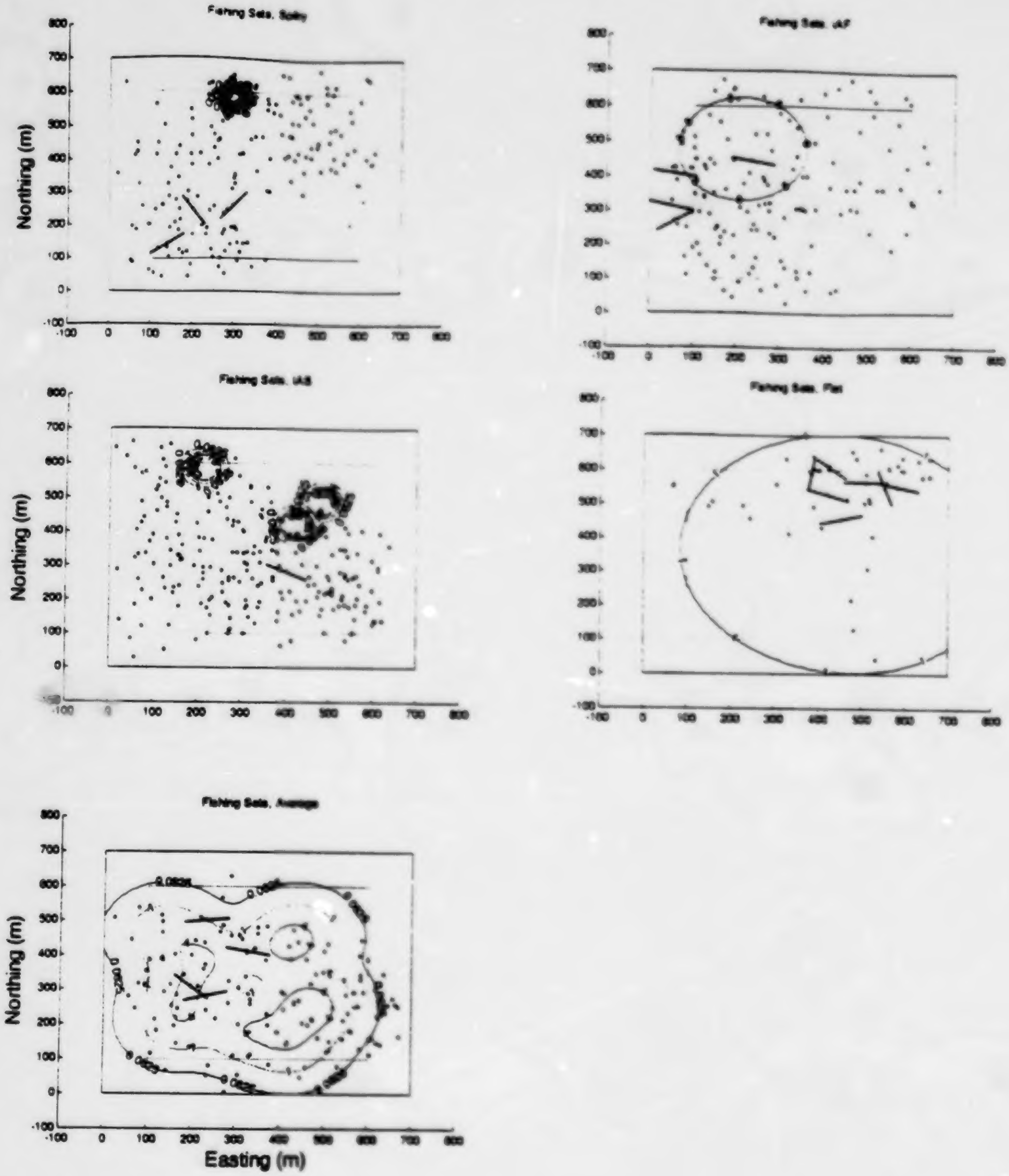


Fig. 42. Sample of distributions tested in simulation with two dimensional contours shown. Solid outer line shows square boundary of search area. Inner red line shows boundaries for centers. Solid blue lines at angles show set locations. Closed circles represent simulated data points collected every 100m.

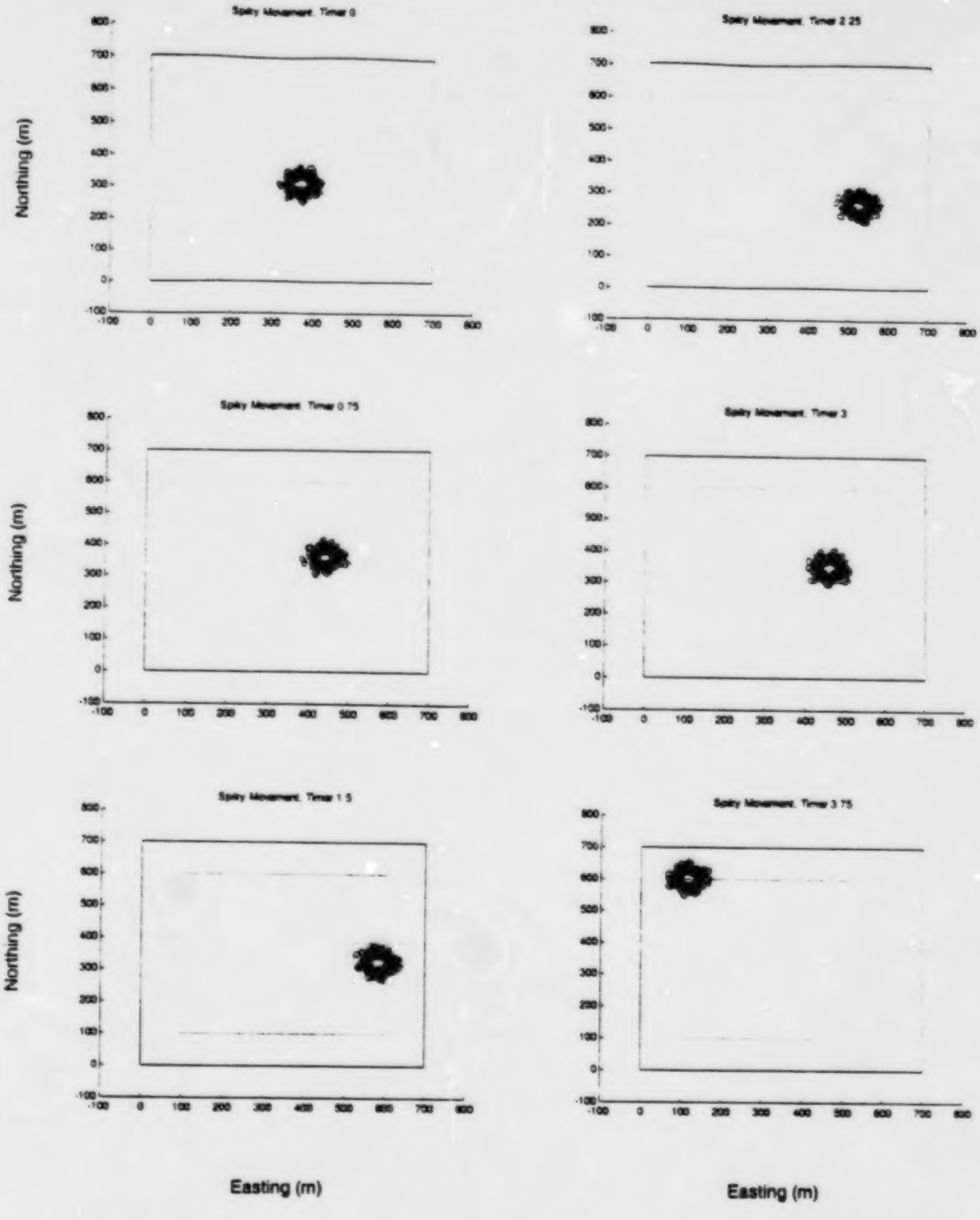
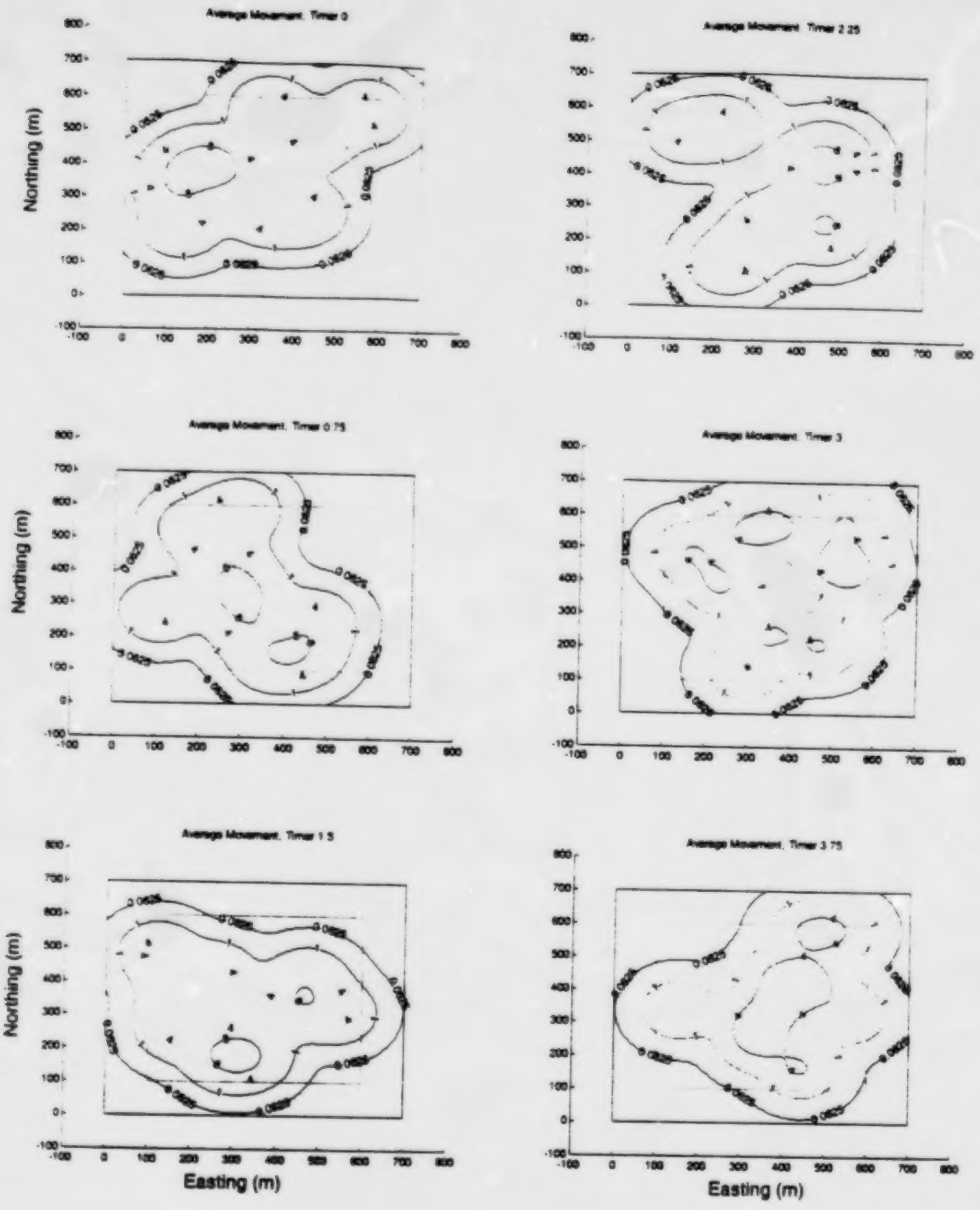


Fig. 44. An example of how the spiky distribution changed position during the simulation.



Average Movement. Time: 0

Average Movement. Time: 2.25

Average Movement. Time: 0.75

Average Movement. Time: 3

Average Movement. Time: 1.5

Average Movement. Time: 3.75

Fig. 45. An example of how the average distribution changed position and shape during the simulation.

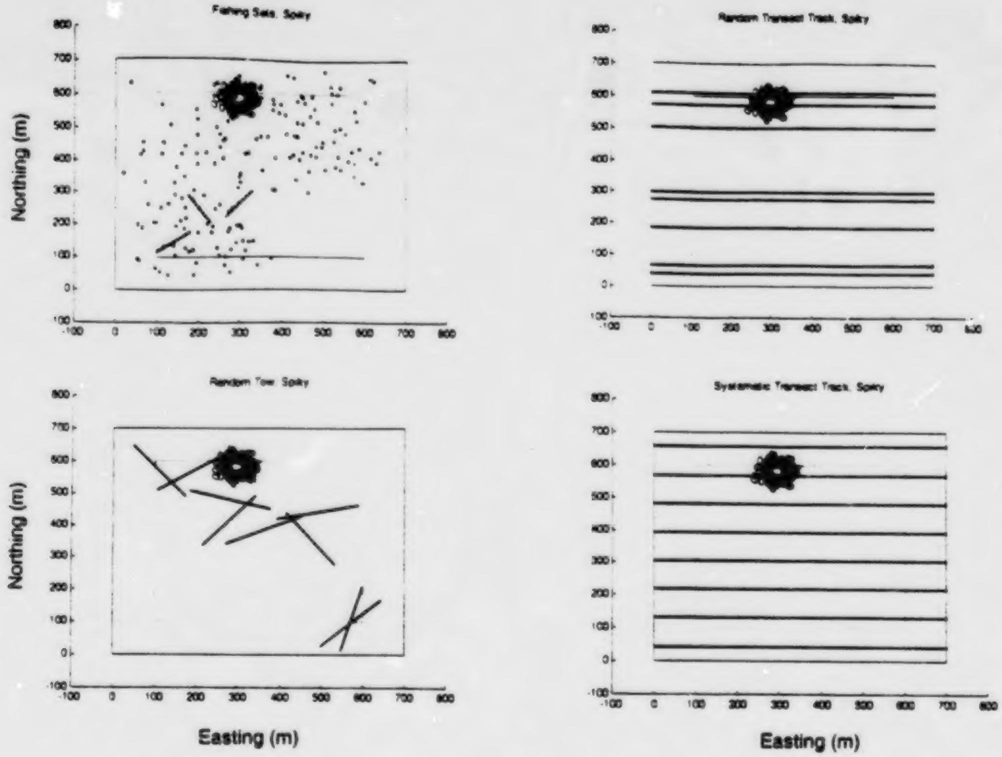


Fig. 46. An example of how boat searching, random tows, random transects, and systematic transects sampled the spiky distribution during the simulation. For the 'Fishing Sets' figure (upper left); closed circles represent acoustic simulated data point locations and lines represent fishing set locations.

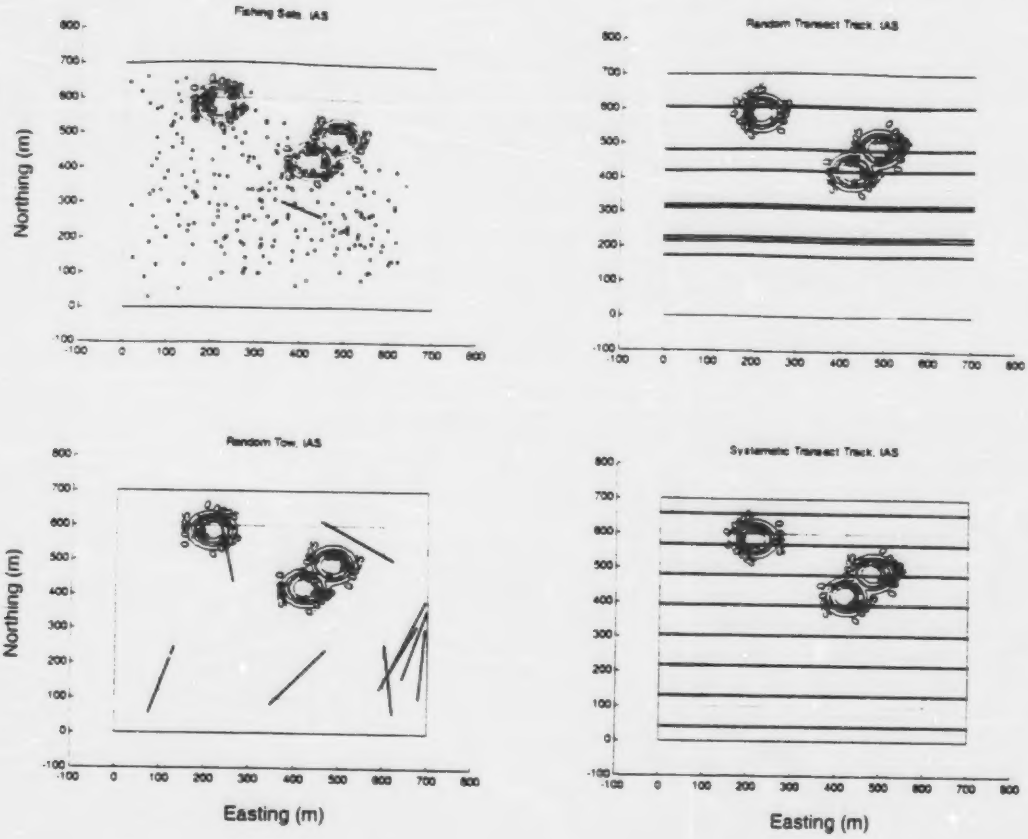


Fig. 47. An example of how boat searching, random tows, random transects, and systematic transects sampled the IAS (intermediate between spiky and average) distribution during the simulation. For the 'Fishing Sets' figure (upper left); closed circles represent acoustic simulated data point locations and lines represent fishing set locations.

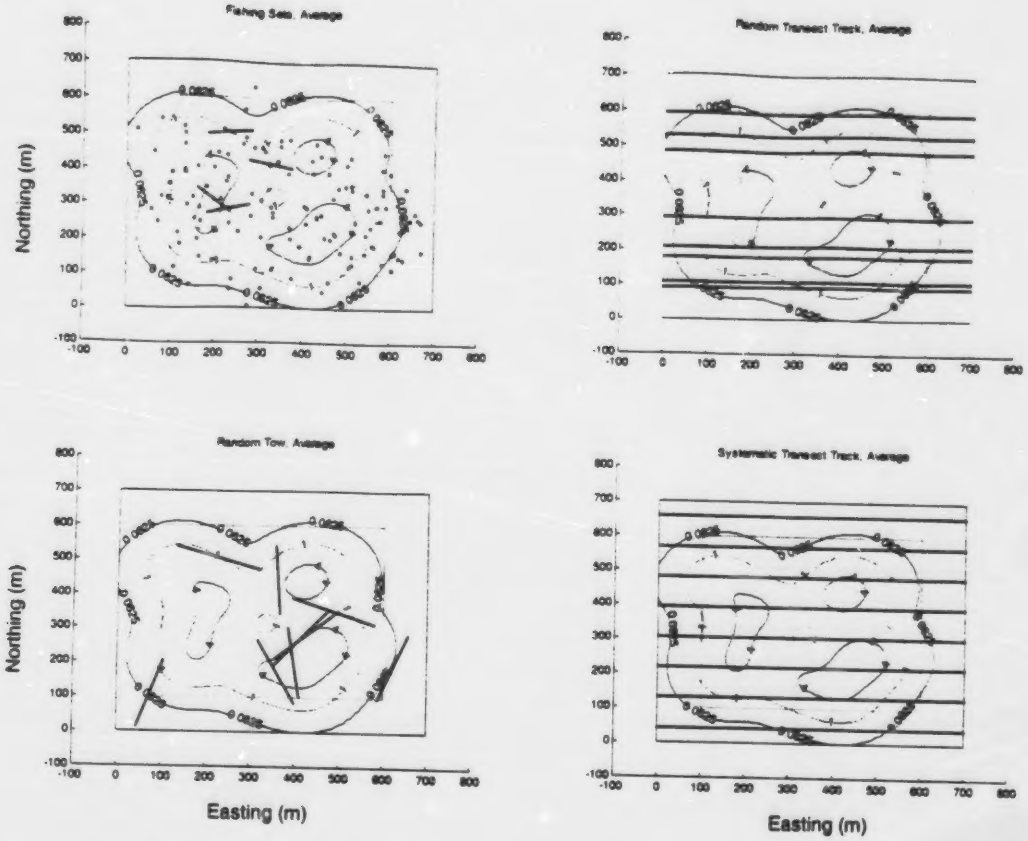


Fig. 48. An example of how boat searching, random tows, random transects, and systematic transects sampled the average distribution during the simulation. For the 'Fishing Sets' figure (upper left); closed circles represent acoustic simulated data point locations and lines represent fishing set locations.

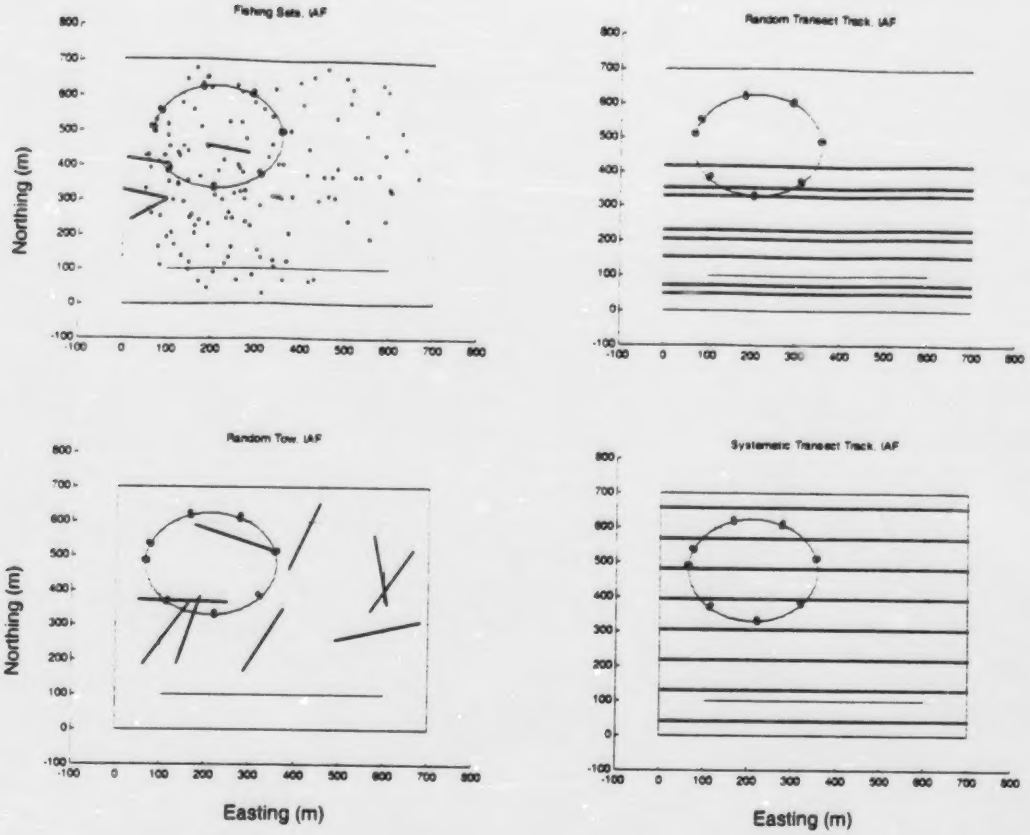


Fig. 49. An example of how boat searching, random tows, random transects, and systematic transects sampled the IAF (intermediate between flat and average) distribution during the simulation. For the 'Fishing Sets' figure (upper left); closed circles represent acoustic simulated data point locations and lines represent fishing set locations.

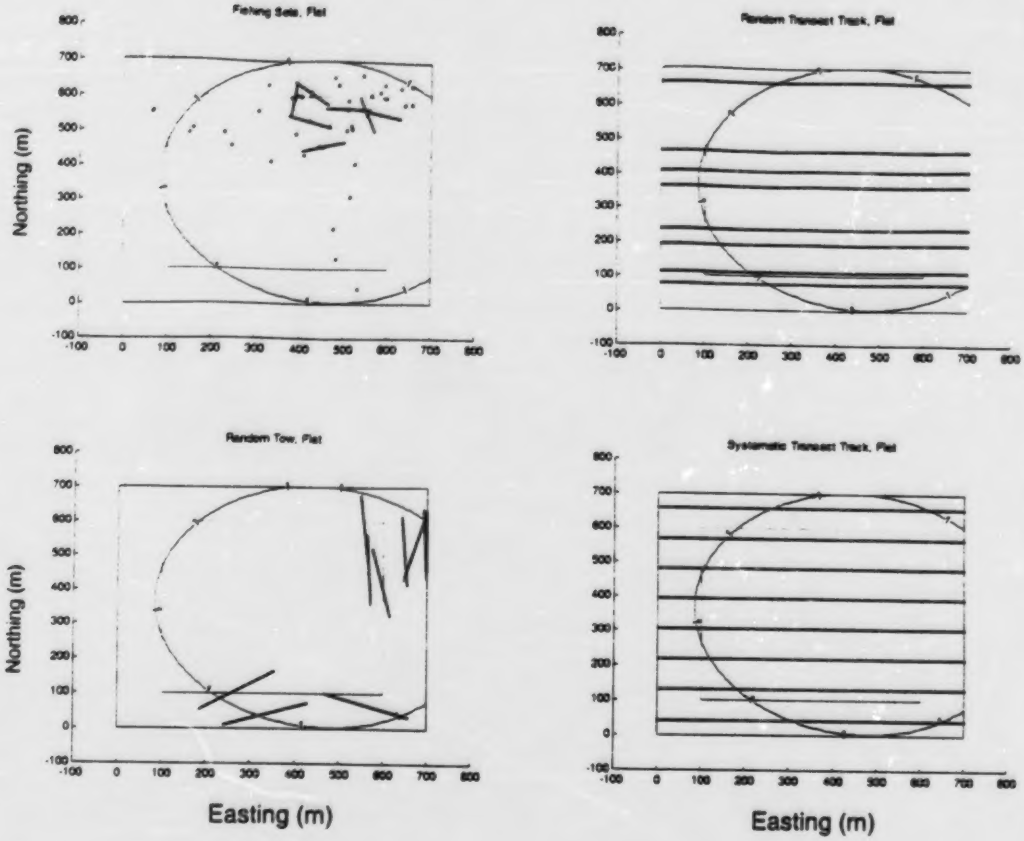


Fig. 50. An example of how boat searching, random tows, random transects, and systematic transects sampled the flat distribution during the simulation. For the 'Fishing Sets' figure (upper left); closed circles represent acoustic simulated data point locations and lines represent fishing set locations.

6.8 Simulated searching data

The acoustic boat started collecting simulated data at the edge of the search area, either on the left hand side, (x=0, y=minimum to maximum), or the bottom edge, (x= minimum to maximum, y=0). It was not necessary to consider the other two outer edges by symmetry of the distributions (Figs. 46-50). The acoustic boat moved 100 metres at each sampling or clock interval. The searching method consisted of random and directed searches. The turning direction of the simulated acoustic boat was determined by the change in density of fish observed over each 100 metre increment. The decision on turning angle was made every 200 metres for random searches and every 100 metres during the directed search. Regardless of when the turning angle decision occurred, simulated data were stored every 100 metres as in the real data set. The average density over this increment was determined by numerical integration (Appendix 2).

Searching for each simulation began by collecting simulated data during a random search for 20 time intervals. A decision on turning direction was made every 200 metres. The direction of turning at each of these decision points was randomly selected from 0 to 360 degrees. After this initial random search period the directed search algorithm was initiated. The direction of turning was based on the slope of the simulated data points collected at 20 metre increments along the 100 metre search track increment. For example, if the slope and hence, biomass was increasing along the track then, the boat tended to keep going in the current direction. If the slope and biomass were decreasing then the boat tended to turn back towards the direction it had just been searching. If the slope was near zero (-0.5 to 0.5 kg/m) then the boat would make a right or left turn at approximately a right angle. The angle of the turn was determined by the magnitude of the slope and the direction (left or right) of the turn was randomly determined (Appendix 2).

Using these rules, the boat would tend to circle in one spot if it found a peak in the distribution. These cases were detected by recording the number of times the slope alternated between positive and negative slopes greater than an absolute value of 0.1 kg/m. If the boat encountered a succession of 7 positive and negative slopes then the boat was directed to fish, or if the boat limit had already been caught, then they began searching randomly for another 20 time intervals. In both these cases, the direction of the first turn was towards the highest density observed up to that point. If at any time a turn took the boat out of the search area, a new angle and direction were randomly chosen until the next turn was in the search area.

Simulated data were collected from the searching activity for the total simulated time period (four hours). Three indices were derived from these simulated data. The first included all the simulated search data (Searching - Total) and the second included only simulated data collected up to the time the boat limit was caught (Searching - Fishing). Biomass indices from these two sets of simulated data were determined using voronoi polygons as described below. In addition, the arithmetic average of the density in the Searching - Total simulated data set was used to derive a biomass index. As a result, indices from six simulated data collection methods were compared: Searching - Total, Searching - Fishing, Arithmetic, Random Tows, Random Transects, and Systematic Transects.

6.9 Simulated fishing

To determine the effect that depleting the resource had on the development of biomass indices, a simulated fishery was included in the model. Depletion occurred from simulated fishing by the acoustic boat and the gillnet fleet. Natural mortality was assumed to be zero during the fishing period. The searching simulation for the rest of the fleet applied rules to the entire fleet rather than to individual boats as was done for the simulated acoustic boat data collection. Fishing locations for the fleet were selected using a cumulative distribution of fish density and was consistent with the ability of captains to locate higher than average densities for fishing (Fig. 41; Appendix 2). However, catches for the fleet and the acoustic boat were calculated in the same manner and were a function of net length, net influence width, local catchability, and stock density at the fishing location in both cases. These parameters were equal for each type of boat. For the acoustic boat, the stock at the fishing location was estimated using numerical integration over the net length. For the fishing fleet, the point of the fishing location (described below) was used and this value was assumed to be the average over the net length. This simplifying assumption was made to save computation time. Fishing depleted the overall stock on a cluster by cluster basis. Each cluster was depleted in proportion to its contribution to the density at the fishing location. Thus, if fishing occurred at the centre of one cluster but at the edge of another, most of the fish would be removed from the cluster which had the fishing near its centre (Appendix 2).

Catch rates from the Pictou fishery and simulated acoustic boat and fleets were described as functions of density using von Bertalanffy curves (Quinn and Deriso 1999). SAS (1999) Proc NLIN was used to estimate the model parameters and r^2 values.

6.10 Acoustic boat simulation

Fishing by the simulated acoustic boat occurred only during a directed search and only when certain conditions associated with the density of the stock and the slope were met. Fishing occurred if the boat was at a density very similar to the highest so far observed by the boat during the night. Fishing could occur at a lower density if the slope was below a critical negative value, or if the boat had gone over the area 7 times as described above. In addition, if no fishing had occurred during the first half of the night, then the critical density threshold for fishing was lowered (Appendix 2). Fishing by the acoustic boat continued until the boat limit was caught or the allotted four-hour time limit was reached. After the boat limit was caught the acoustic boat continued to collect simulated data under the searching rules but would not fish. Each fishing event took 30 minutes. During this time, simulated data collection by the boat stopped to simulate the time required for the net to be set and hauled. After each fishing event the boat would search randomly for 20 *x* 0.015 hours or 18 minutes before beginning the directed search again.

6.11 Fleet fishing simulation

The simulation time interval between fishing events for the fleet was 30 minutes, the average time to set and haul nets. There were eight fishing events spread evenly through the four-hour searching period. The fleet size was determined using a function derived from real data (Table 8; Appendix 2). A random effect was added to the fleet size using a random normal distribution with a standard deviation of 10. This standard deviation was chosen iteratively until simulated data that closely resembled the range in boats in the real data was achieved (Appendix 2). Fleet size was fixed so that the minimum number of boats fishing in a night was 10, and the maximum was 120, including the acoustic boat.

The fishing location of each boat in the fleet was a random variable with the density function proportional to the stock density function. Therefore, the fleet had a tendency to fish at the higher densities (Fig. 51).

There were 8 fleet fishing events throughout the night but not each vessel fished at each event. The proportion of the fleet that fished at each event was determined using the simulated data from the acoustic boat. Three nights of fishing simulated data were collected from the acoustic boat during each simulation at a given stock size and condition. The average number of sets made by the acoustic boat during these three trips was used to determine the initial proportion of the fleet fishing on each trip (Appendix 2). This average was updated throughout the simulation for each stock size, distribution, and fishing - movement condition. The simulated data from the first three trips were not used in any analysis.

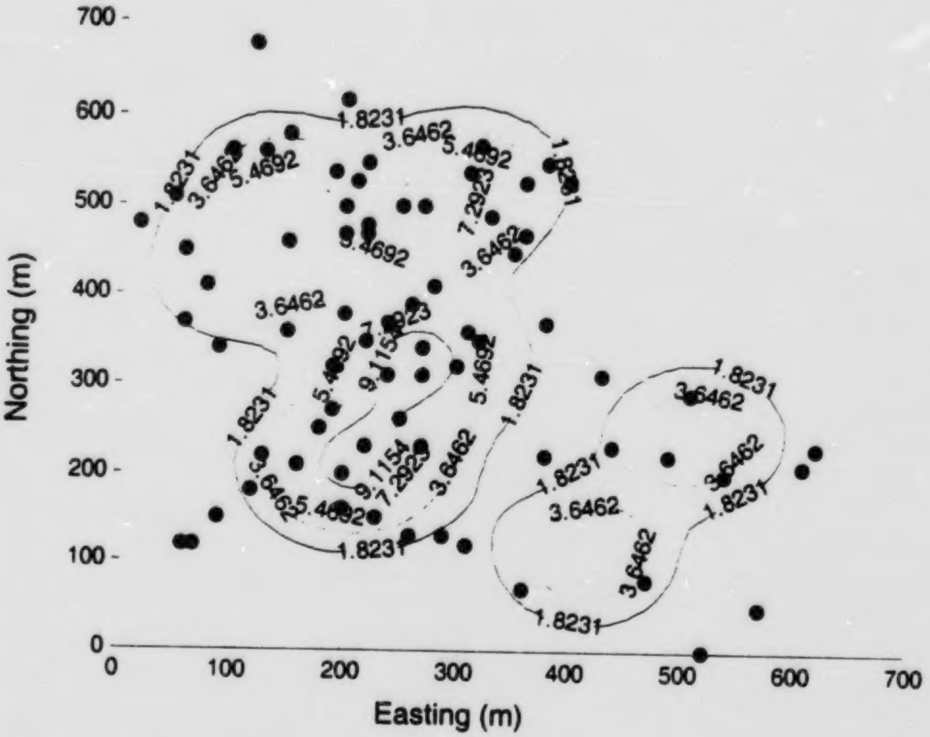


Fig. 51. Distribution of simulated fishing fleet on average distribution. Contour scales differ from other figures.

6.12 Simulated survey indices

Biomass indices from the simulated surveys were determined by taking the arithmetic average of the simulated data points collected during each of the surveys and expanding these densities to the area surveyed. Spatial statistical methods (eg. voronoi polygons) were not applied to the simulated survey data because survey positions were not systematically biased toward collecting simulated data at locations of highest fish density.

6.13 Simulated fishery acoustic indices - voronoi polygons

Voronoi polygons have been defined earlier (Chapter 5). The only change in the methodology for this simulation was in defining the exterior boundaries of the simulated data points. In the analysis of the simulated data, polygons drawn around each outside simulated data point defined this boundary (Figs. 23, 24). This was not practical for the simulation and the convex hull was used to define the exterior boundary of the simulated data points. The convex hull was delineated and used to derive the voronoi polygons as described below.

Many voronoi polygon algorithms do not use the outermost points in forming or defining the boundaries of the polygons (Green and Sibson 1978; Boots and Murdoch 1983; Byers 1992). An exception, however, is VERTICAL MAPPER (1998) but its routines were not amenable to incorporation into the simulation model. MATLAB (1998, ver 5.3) routines were altered and written in order to use the convex hull as the outermost defining boundary for the polygons.

The first step in this analysis was to average the density and location values that were within one metre of each other. The second step was to identify the convex hull. This identification was done using the MATLAB (1998, ver 5.3) convhull function. This hull was expanded by 20 metres in order to include the convex hull points in the voronoi polygons, a procedure described by Cressie (1991). Voronoi polygons were then determined using the MATLAB (1998, ver 5.3) voronoi function altered to output voronoi edge coordinates, Delaunay triangle indices, and circle centre indices. This function produced some voronoi polygons whose vertices were outside the convex hull. The intersection points between the polygon edges and the convex hull were found and these points were substituted for the vertices that were outside the convex hull. As a result, the convex hull defined the outer edge of the voronoi polygons (Fig. 52).

The area of each polygon was found using the MATLAB (1998, ver 5.3) polyarea function and the biomass in each polygon was determined by multiplying the density of the simulated data point by the area. The sum of these biomass estimates formed the biomass index. If the boat limit was caught before the end of the four hours, the simulated data collection usually covered a smaller portion of the search area (Fig. 53).

6.14 Evaluating simulated indices

Two methods were examined for evaluating simulated indices. The first determined the slope between the estimated biomass and true stock and the slope between the standard deviation of the estimated biomass at each stock size. The best indices would not necessarily have a one-one relationship with true stock, but would have a relatively precise and linear relationship regardless of the distribution, fishing, or movement condition. That is, when the slopes of biomass are plotted against distribution type for each condition, the best indices would have a positive slope and little variation around the regression line.

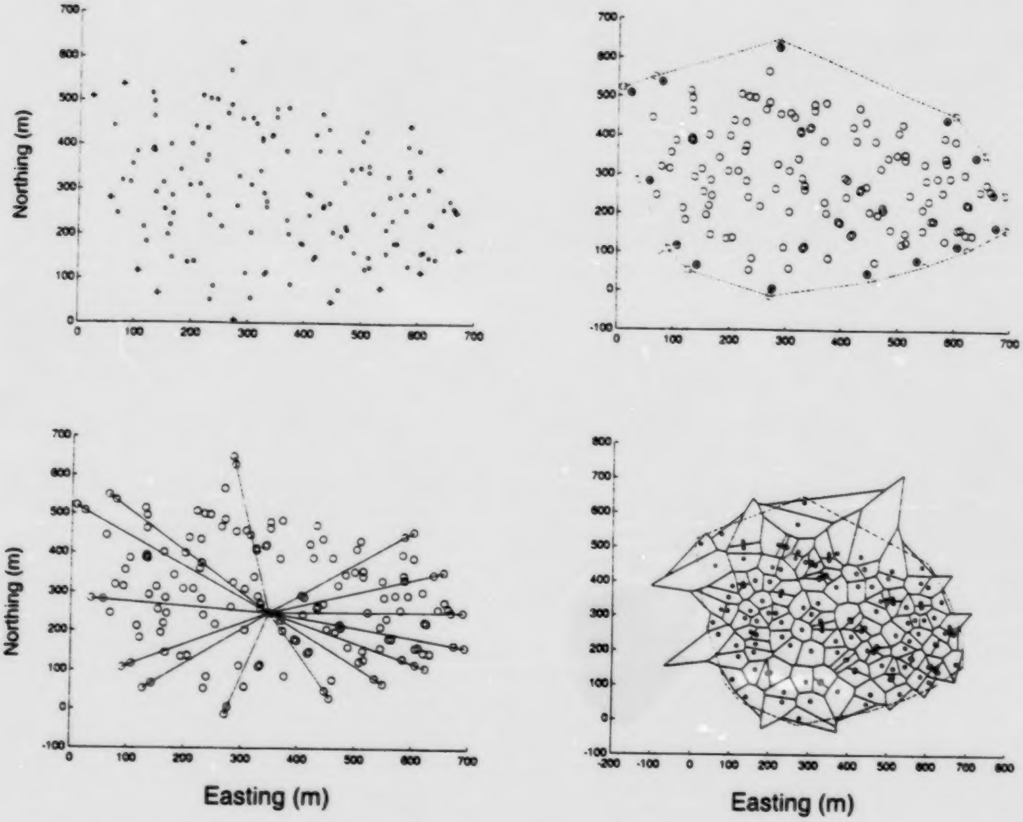
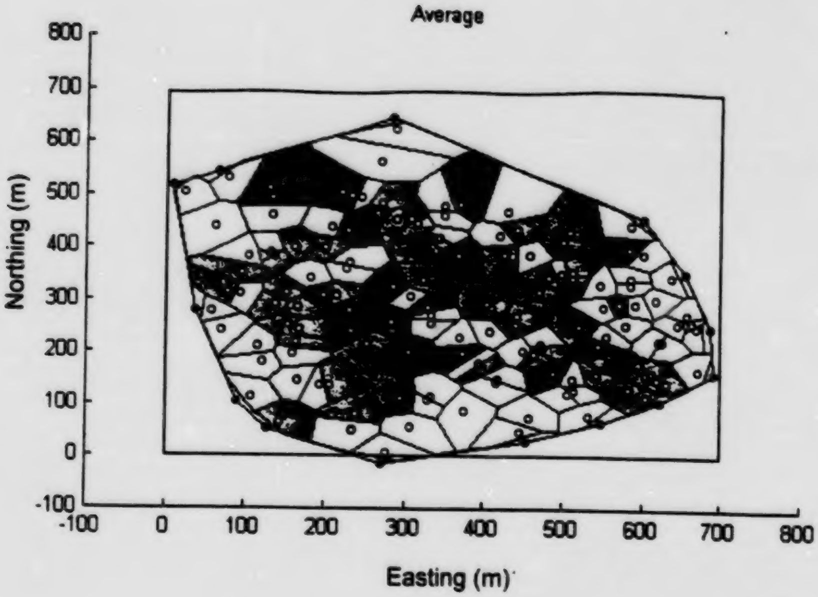


Fig. 52. An example of how the convex hull was defined to create the voronoi diagrams. Simulated data points (upper left), simulated data points defining the original and exanded hull (lower left), creating a new hull (upper right), deriving the voronoi polygons and finding the intersection points with the hull to create a voronoi diagram with the convex hull as the outer boundary (lower right).



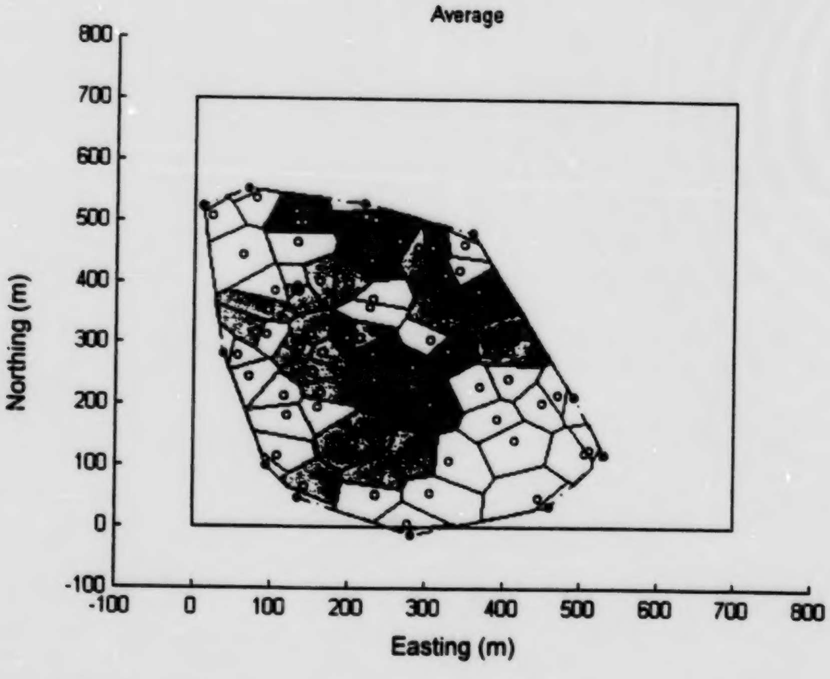


Fig. 53. Examples of voronoi diagrams used to estimate biomass. Searching – Total (upper) and Searching – Fishing (lower) for an average distribution.

The second method, closed loop (Anon 1998), for evaluating the simulated indices, compared exploitation rates that would result from managing the simulated fishery assuming that the indices did represent a one-one relationship with the true biomass. For example, what would the true exploitation rate be if the target fishing mortality was 20% and a quota was set as 20% of the estimated biomass, given that the true simulated biomass is known. This comparison was made using the average exploitation rate that would result at each stock size and by determining the percentage of exploitation rates that would be > double the 20% target. This method was only examined for the Movement – Fishing condition.

The closed loop evaluations indicate the magnitude of the mistakes that would be made using each index. Such evaluations are one way of taking into account the variability in the estimates, of evaluating one index against another, or of evaluating the cost effectiveness of collecting data for the different indices.

6.15 Exploitation rates and the importance of distribution

Catch in the simulated fishery was controlled only by the nightly boat limit. The distribution of exploitation rates was determined for each stock size and fish distribution by dividing the catch by the true stock size. These exploitation rates were calculated only for the Movement – Fishing condition. To determine the relationship between the variance of the point densities measured by each index method and the area with 75% of the stock, the mean variance over all stock sizes at each condition was plotted against the area with 75% of the stock.

6.16 Model validation - Catch rate acoustic boat

A comparison was made between the catches and catch rates (kg/nets), from the acoustic boat collecting data during the Pictou 1997 gillnet fishery with those obtained from the simulated acoustic boat. This comparison indicates that the simulated values are consistent with those from the 1997 fishery. Trip catches from the acoustic boat collecting data during the Pictou and the simulated fishery were low and rose quickly to an asymptote consistent with the boat limit at densities > 2 kg/m^2 (Fig. 54). The exceptions were catches for the simulated spiky distribution, because sometimes the spike was missed entirely resulting in low catches at all densities (Fig. 54).

Similar trends were observed for catch rates (CPUE). The catch rates from the acoustic boat reached an asymptote slightly below the maximum that would occur if the boat limit were caught each time (1500 kg/net). The exception was the spiky distribution (Fig. 54).

With the exception of the spiky distribution, the number of sets made each night in the fishery by the acoustic boat, or by the simulated acoustic boat, declined with increasing density. This finding is consistent with the expectation that fewer sets should be necessary as density increases (Fig. 54).

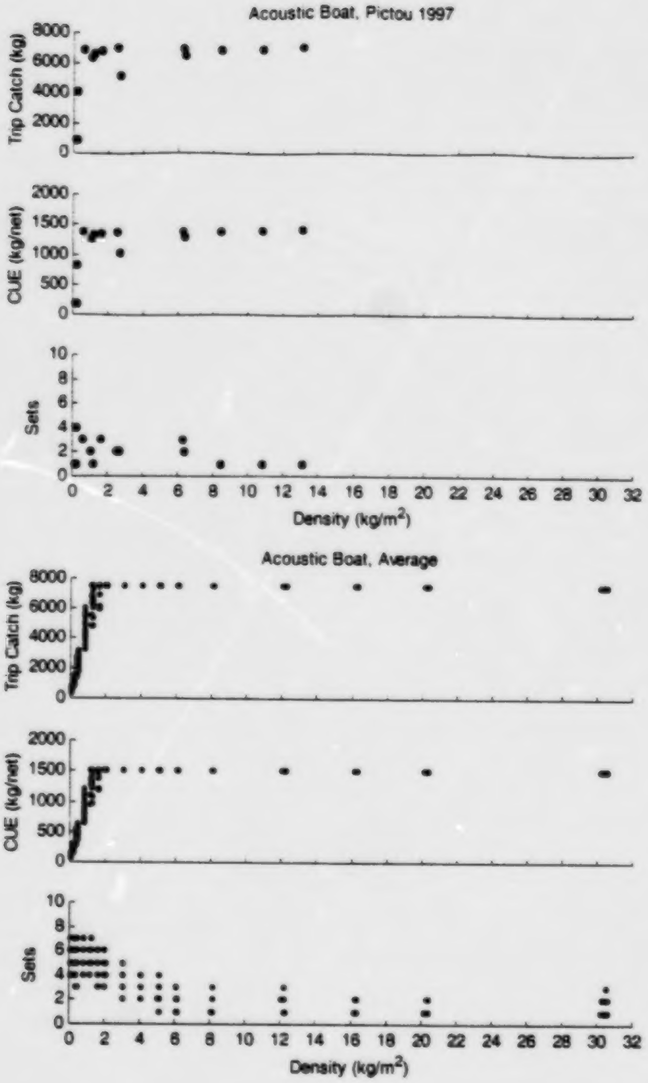


Fig. 54. A comparison of catch and effort data from the boat collecting acoustic data at Pictou, Nova Scotia, 1997 compared to the simulated acoustic boat at various distributions.

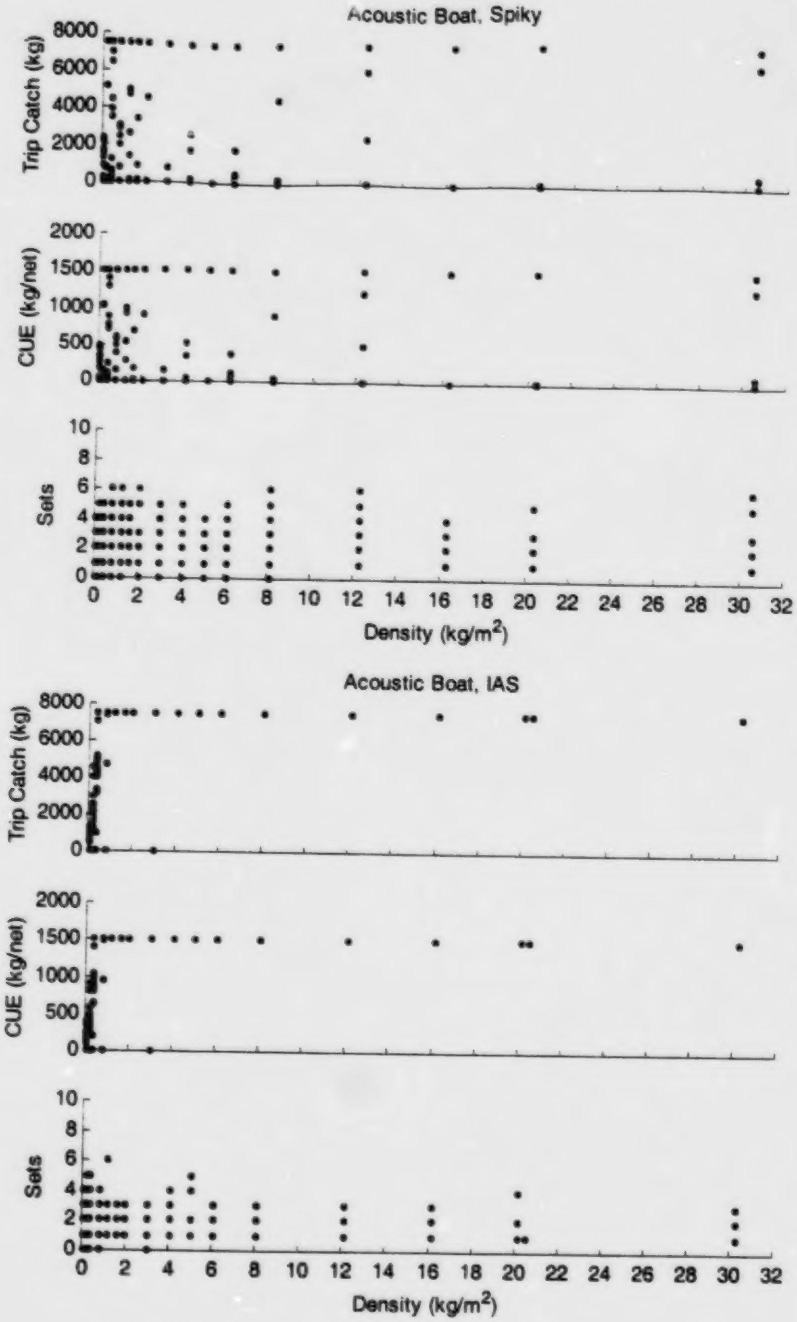
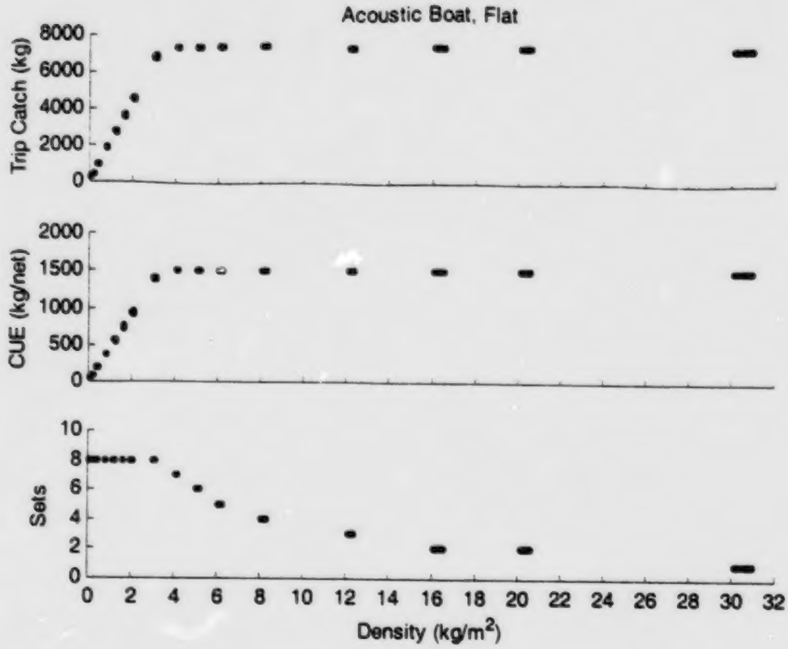

Acoustic Boat, Spiky
Trip Catch (kg)
8000
6000
4000
2000
0
CUE (kg/net)
2000
1500
1000
500
0
Sets
10
8
6
4
2
0
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32
Density (kg/m2)
Acoustic Boat, IAS
Trip Catch (kg)
8000
6000
4000
2000
0
CUE (kg/net)
2000
1500
1000
500
0
Sets
10
8
6
4
2
0
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32
Density (kg/m2)

Fig. 54 (cont.).


Acoustic Boat, Flat
Trip Catch (kg)
8000
6000
4000
2000
0
CUE (kg/net)
2000
1500
1000
500
0
Sets
10
8
6
4
2
0
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
Density (kg/m²)

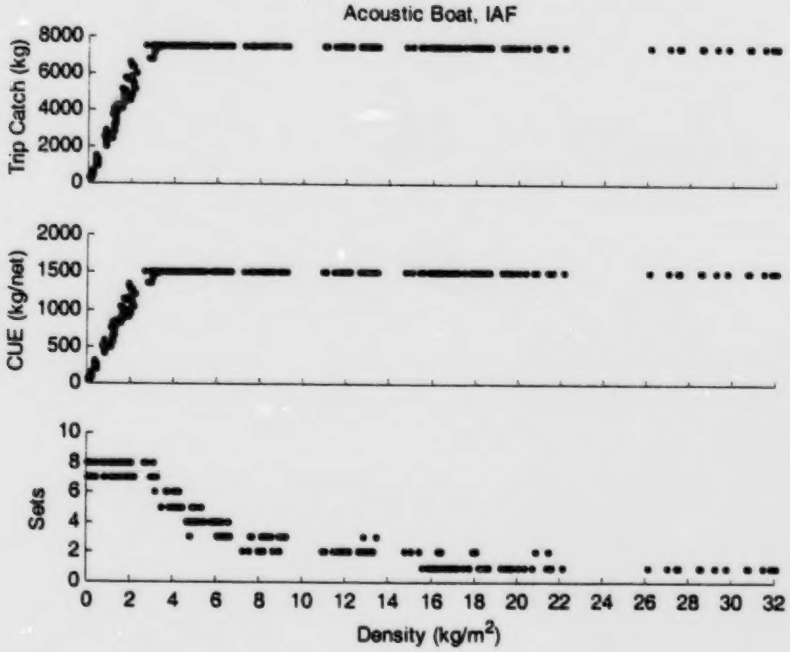

Acoustic Boat, IAF
Trip Catch (kg)
8000
6000
4000
2000
0
CUE (kg/net)
2000
1500
1000
500
0
Sets
10
8
6
4
2
0
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
Density (kg/m²)

Fig. 54 (cont.).

6.17 Model validation - Catch rate fleet

A similar consistency was observed between the Pictou fishery fleet catches and the simulated fleet catches. Catches in the Pictou fishery tended to increase steadily with fish density for density < 6 kg/m^2. Catches by the simulated fleet increased similarly and reached an asymptote for densities exceeding 6 kg/m^2. This similarity was true for all the distributions (Fig. 55). Simulated catch rates showed an asymptote near the boat limit at 4 kg/m^2 or less for all distributions and in the Pictou fishery (Fig. 55). The number of sets tended to decrease as density increased in the simulated fishery (Fig. 55).

6.18 Catch rate models - Acoustic boat and fleet

Parameters from von Bertalanffy models were similar for the Pictou 1997 acoustic boat and the simulated acoustic boat. The model with the greatest difference was for the spiky distribution which had a lower asymptotic $CPUE_{\infty}$ value than the others and a lower r^2 value (Table 9). These lower values were probably a function of the difficulty that the simulated acoustic boat occasionally had in finding the spike. The k parameter, describing the rate of increase in CPUE was highest for the Pictou fishery acoustic boat. The x-intercept (d0) is > 0 in all cases indicating that the CPUE will be 0 at low densities (Table 9). The increase in CPUE is most similar between the Pictou Fishery, the IAS, and the average distribution. The flat and IAF distributions show the slowest increase in CPUE with density (Figs. 56, 57).

$CPUE_{\infty}$ estimates for the Pictou and the simulated fleet CPUE were more similar than for the fishery and simulated acoustic boat (Table 10). The increase in CPUE parameters were similar for the Pictou, flat, IAF, and Average distributions (Table 10). All x-intercept values were positive except for the Pictou fleet (Table 10). The correlation was > 0.70 for all tests (Table 10). The most similar curves were for the Pictou 1997, flat, IAF, and average distributions (Figs. 58, 59).

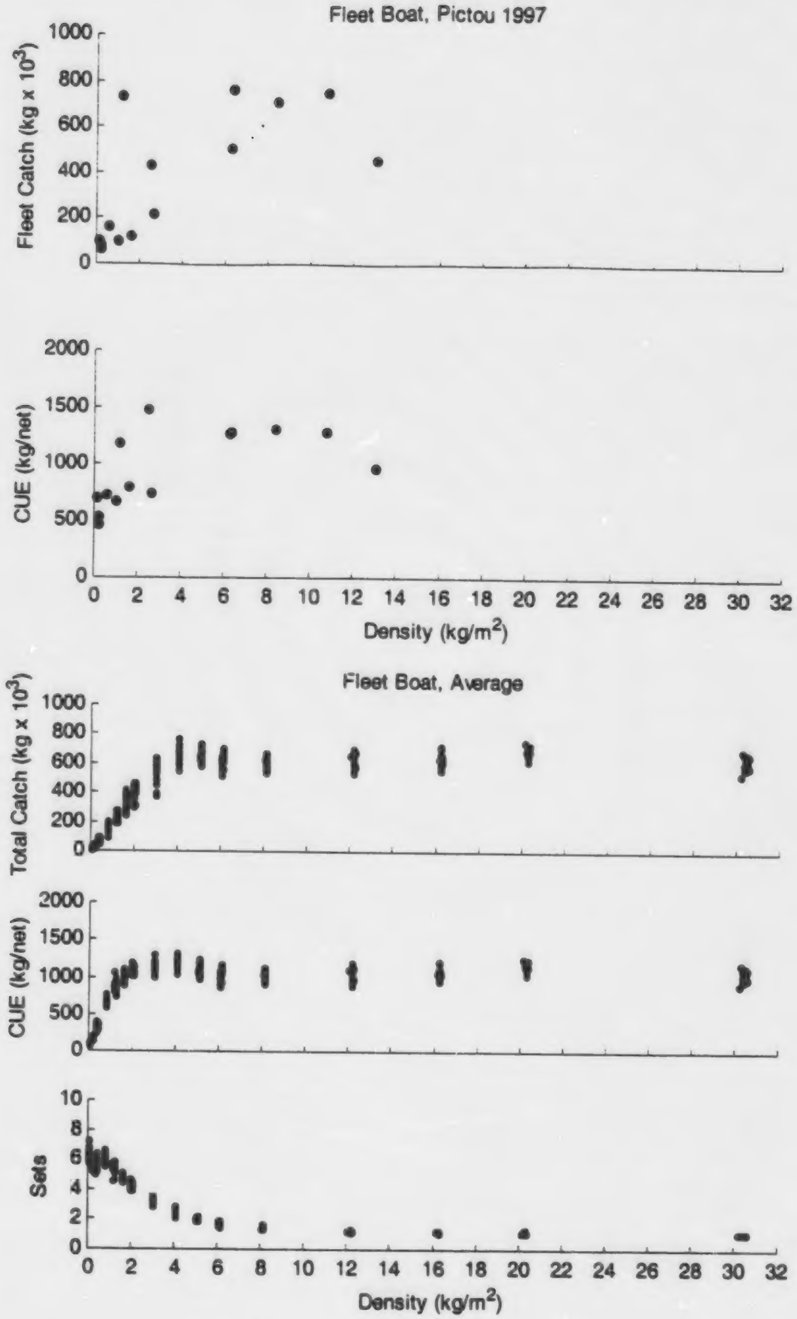


Fig. 55. A comparison of catch and effort data from the fleet fishing at Pictou, Nova Scotia 1997 compared to the simulated fleet at various distributions.

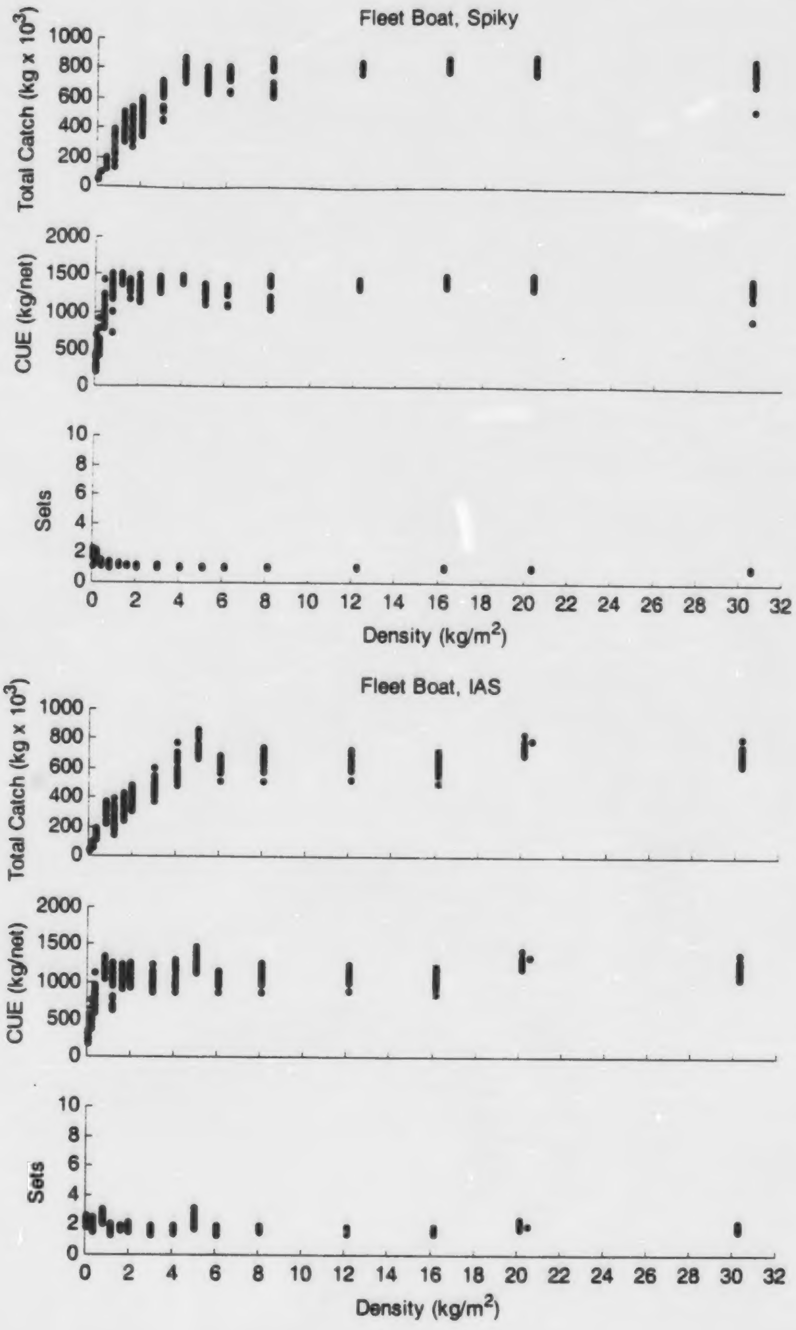
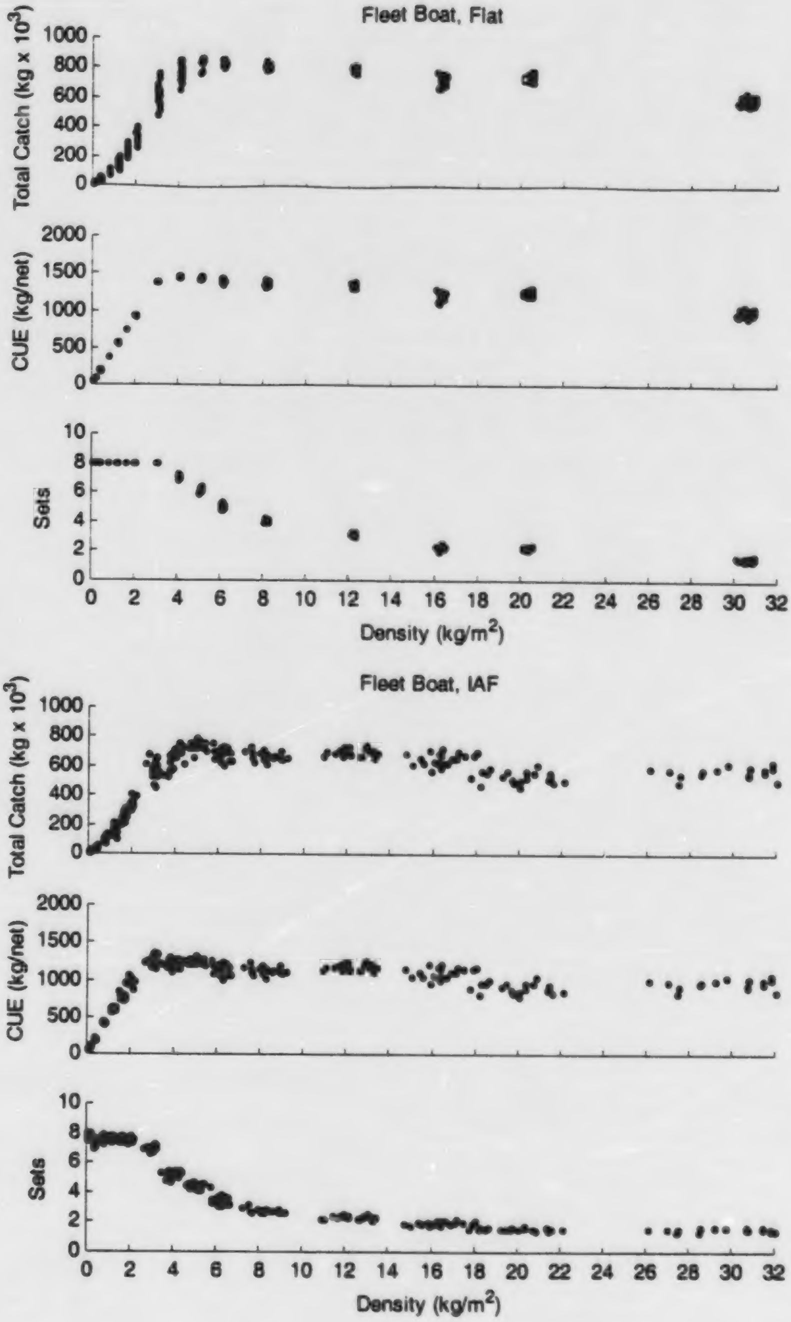

Fleet Boat, Spiky
Total Catch (kg x 10^3)
1000
800
600
400
200
0
CUE (kg/net)
2000
1500
1000
500
0
Sets
10
8
6
4
2
0
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32
Density (kg/m^2)
Fleet Boat, IAS
Total Catch (kg x 10^3)
1000
800
600
400
200
0
CUE (kg/net)
2000
1500
1000
500
0
Sets
10
8
6
4
2
0
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32
Density (kg/m^2)

Fig. 55 (cont.).


Fleet Boat, Flat

Fleet Boat, IAF

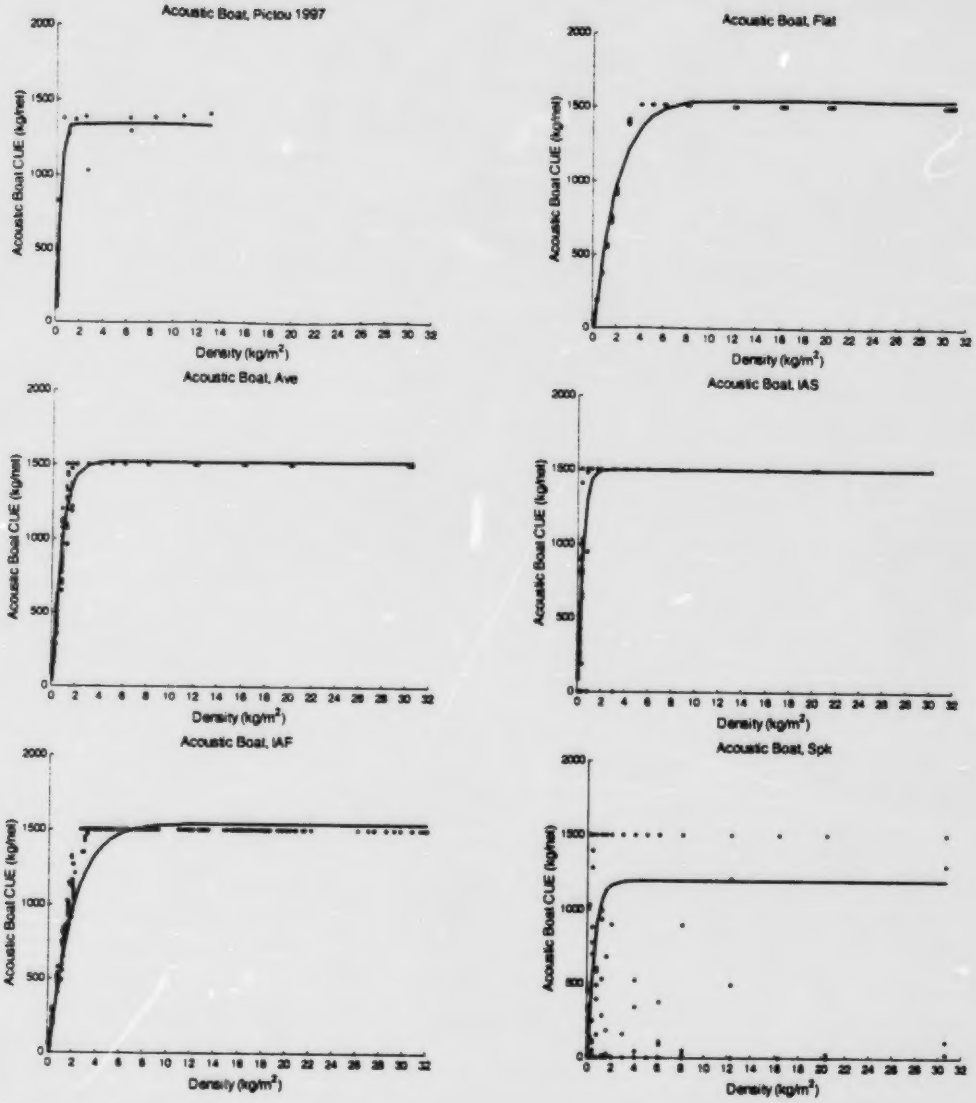
Fig. 55 (cont.)

Table 9. von Bertalanffy parameter estimates and r^2 values for catch rate analysis of boat collecting data during the Pictou, Nova Scotia 1997 fishery and the simulated acoustic boat at various distributions.

Case	CPUEinf	k	d0	r^2
Pictou 97 Acoustic Boat	1336.67	4.22	0.10	0.80
Flat	1544.40	0.53	0.15	0.98
IAF	1531.34	0.67	0.11	0.98
Average	1518.54	1.45	0.09	0.96
IAS	1501.01	2.72	0.06	0.82
Spiky	1195.67	1.95	0.09	0.29

Table 10. von Bertalanffy parameter estimates and r^2 values for catch rate analysis of Pictou, Nova Scotia gillnet fleet, 1997 and simulated fleet catch rates at various distributions.

Case	CPUEinf	K	d0	r^2
Pictou 97 Fleet	1218.29	0.67	-0.74	0.73
Flat	1444.06	0.57	0.15	0.97
IAF	1307.41	0.61	0.10	0.97
Average	1328.18	0.80	0.03	0.96
IAS	1453.12	2.55	0.01	0.97
Spiky	1486.99	3.63	0.02	0.95


Acoustic Boat, Pictou 1997

Acoustic Boat, Flat

Acoustic Boat, Ave

Acoustic Boat, IAS

Acoustic Boat, IAF

Acoustic Boat, Spk

Fig. 56. von Bertalanffy model fits to the relationship between catch rate (kg/net) and fish density for the Pictou, Nova Scotia and simulated acoustic boat. Ave, average; IAF, intermediate between average and flat; IAS, intermediate between average and spiky; Spk, Spiky. R^2 above 0.7 for all except spiky, which was 0.29.

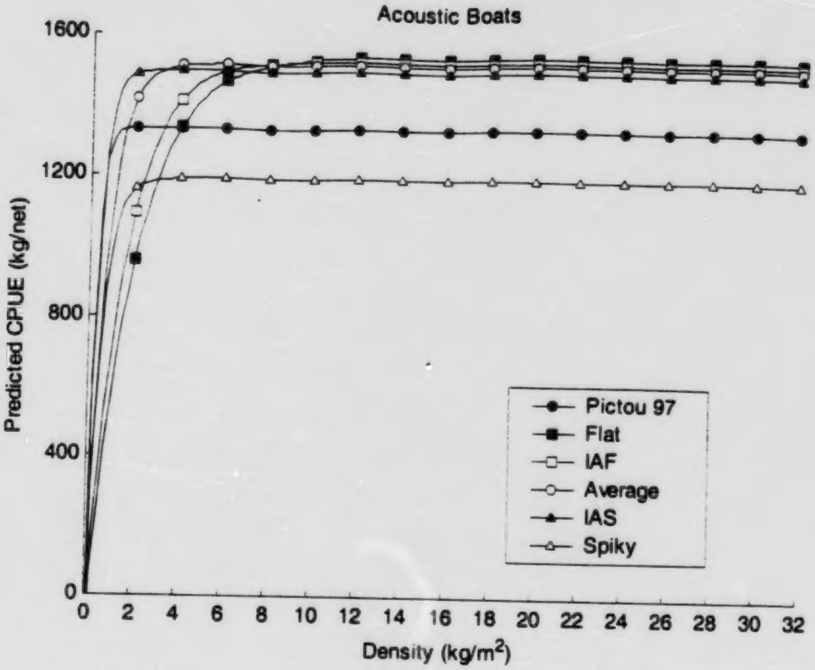


Fig. 57. A comparison of von Bertalanffy model fits to the relationship between catch rate (kg/net) and fish density across all distributions for the Pictou, Nova Scotia and simulated acoustic boat.

6.19 Catch rate per hour - Acoustic boat

Plots of density over time for the simulated data collected from the acoustic boat indicate that more simulated data are collected at higher densities than at lower densities (Fig. 60). This result is a consequence of fewer sets being required to catch the nightly limit at higher densities.

Hours spent fishing in the 1997 Pictou data shows an inverse relationship with density. As density increases the hours spent fishing declines (Fig. 61). This effect was also observed in the simulated distributions except spiky and IAS (Fig. 61). Catch / hour increased steadily in the Pictou 1997 data up to the maximum density observed but in the simulated data it reached an asymptotic level after about 6 or 8 kg/m^2 for most distributions (Fig. 61).

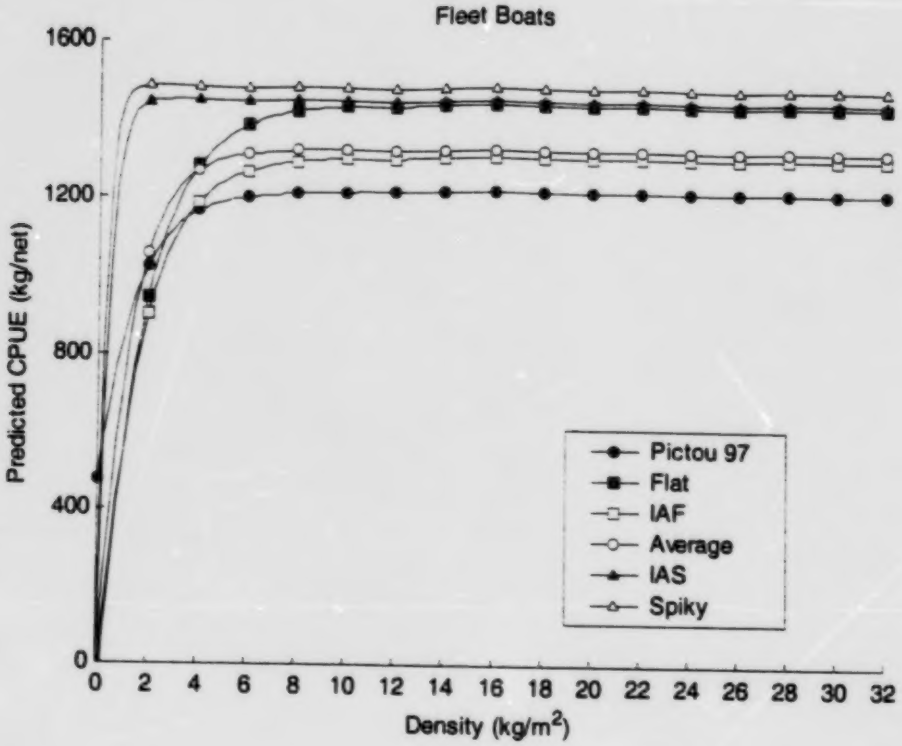


Fig. 58. A comparison of von Bertalanffy model fits to the relationship between catch rate (kg/net) and fish density across all distributions for the Pictou, Nova Scotia and simulated fleet.

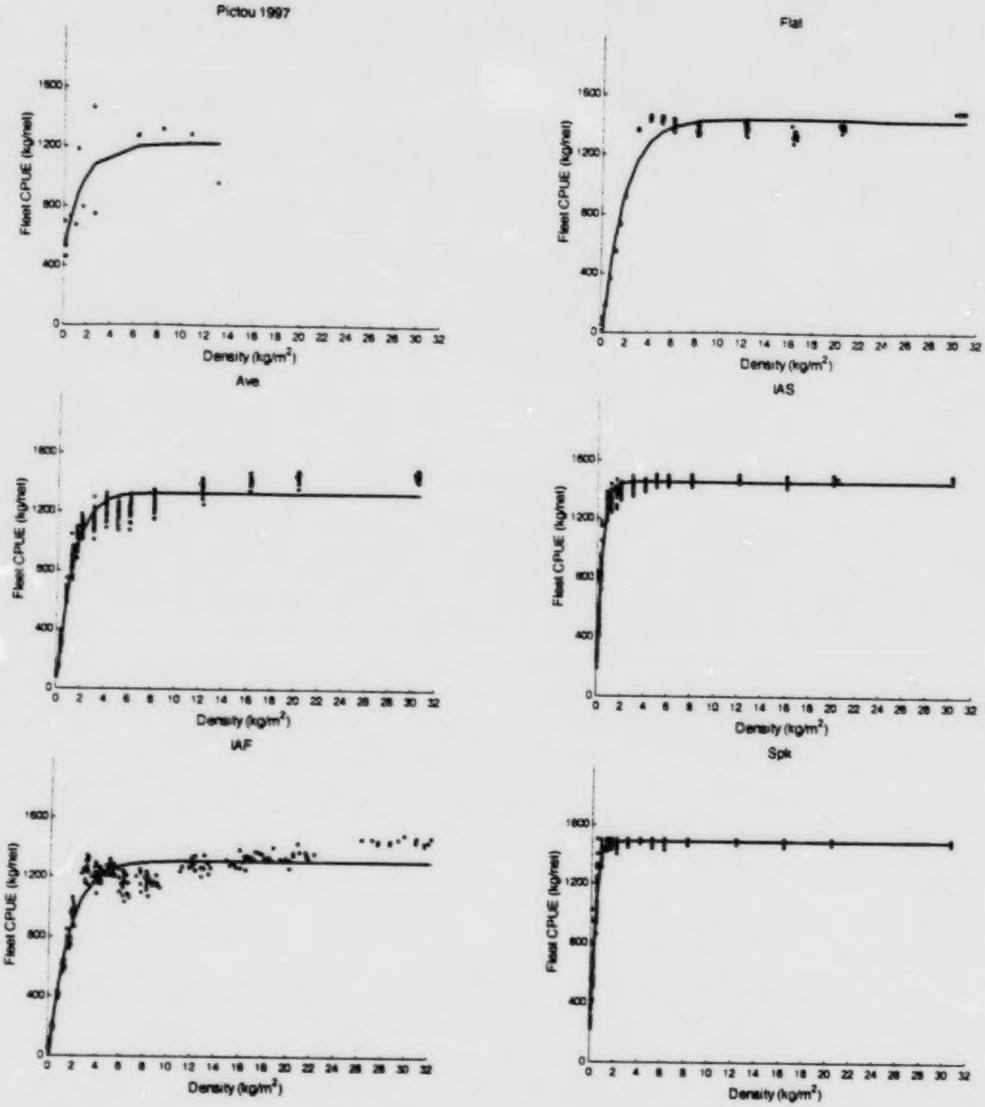


Fig. 59. von Bertalanffy model fits to the relationship between catch rate (kg/net) and fish density for the Pictou, Nova Scotia and simulated fleet. Ave, average; IAF, intermediate between average and flat; IAS, intermediate between average and spiky; Spk, Spiky.

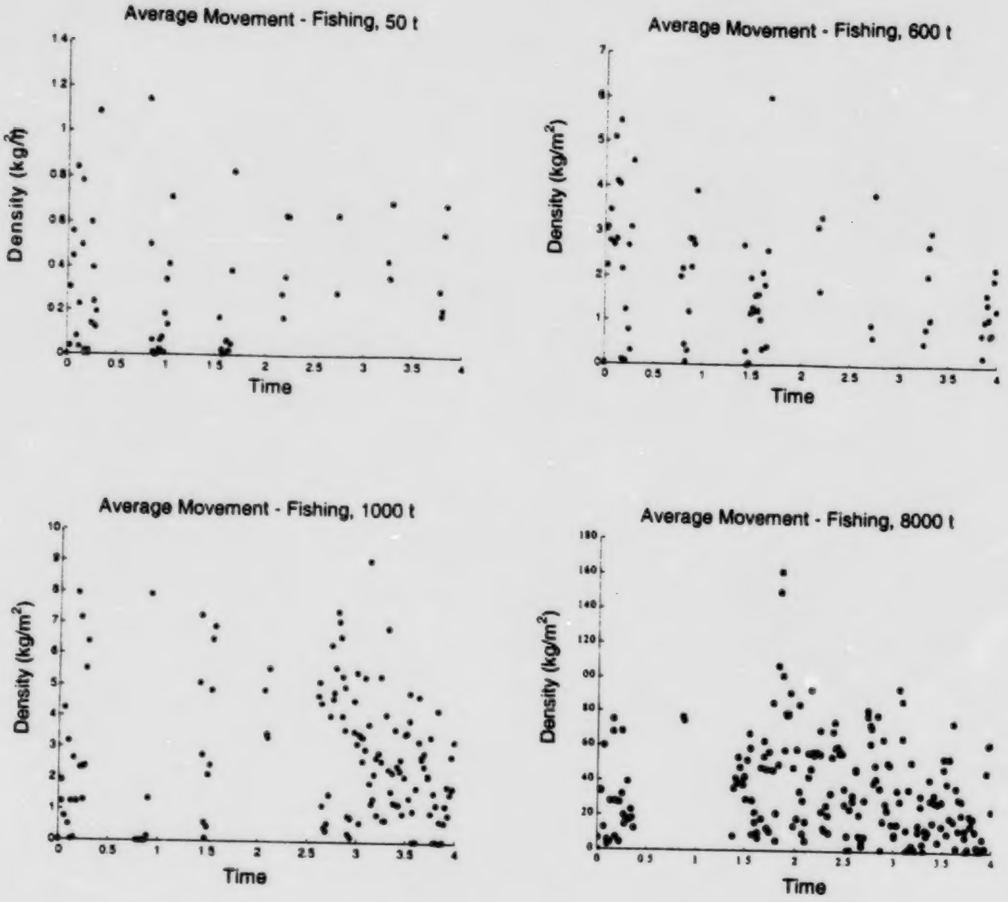


Fig. 60. Examples of how density changed over time for simulations using the average distribution with fishing and movement at the biomass indicated, (t, tonnes).

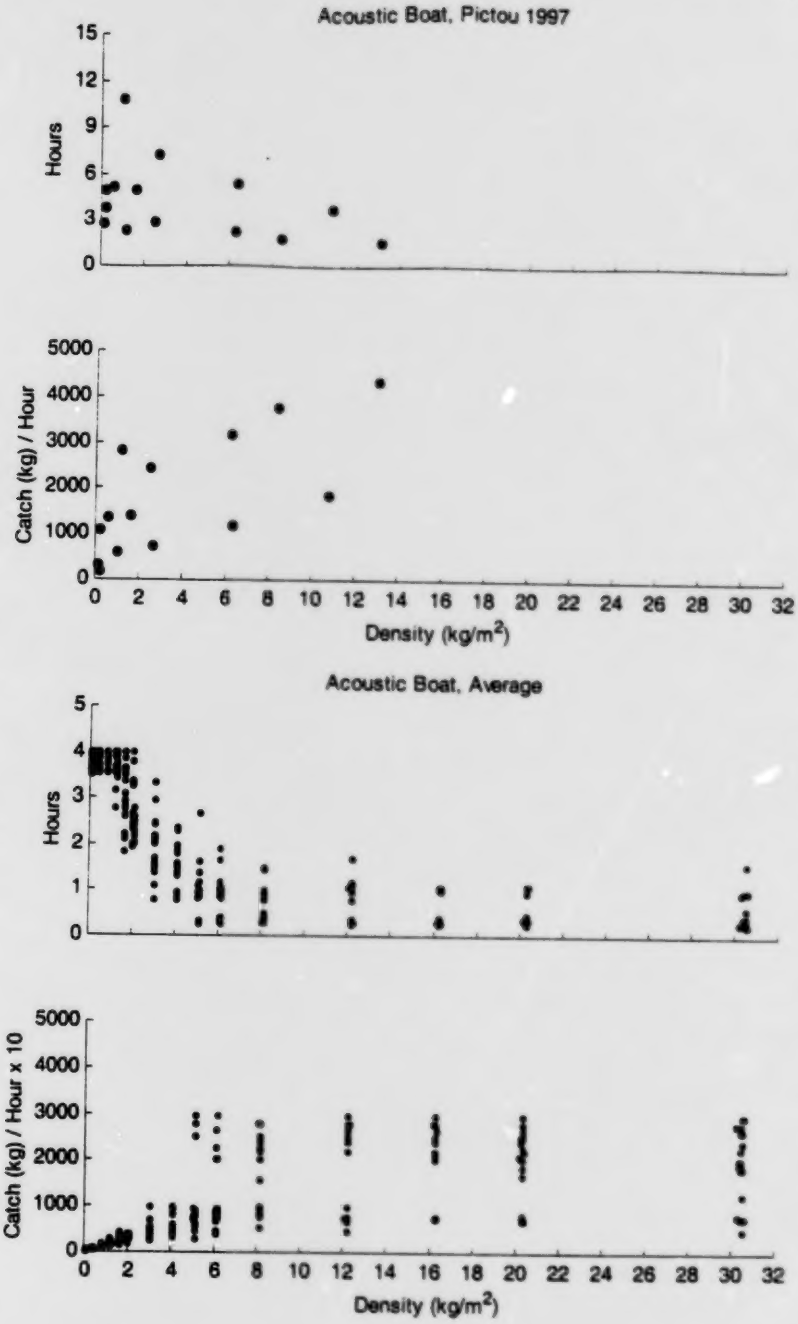


Fig. 61. A comparison of catch / hour from the boat collecting acoustic data at Pictou, Nova Scotia, 1997 compared to the simulated acoustic boat at various distributions.

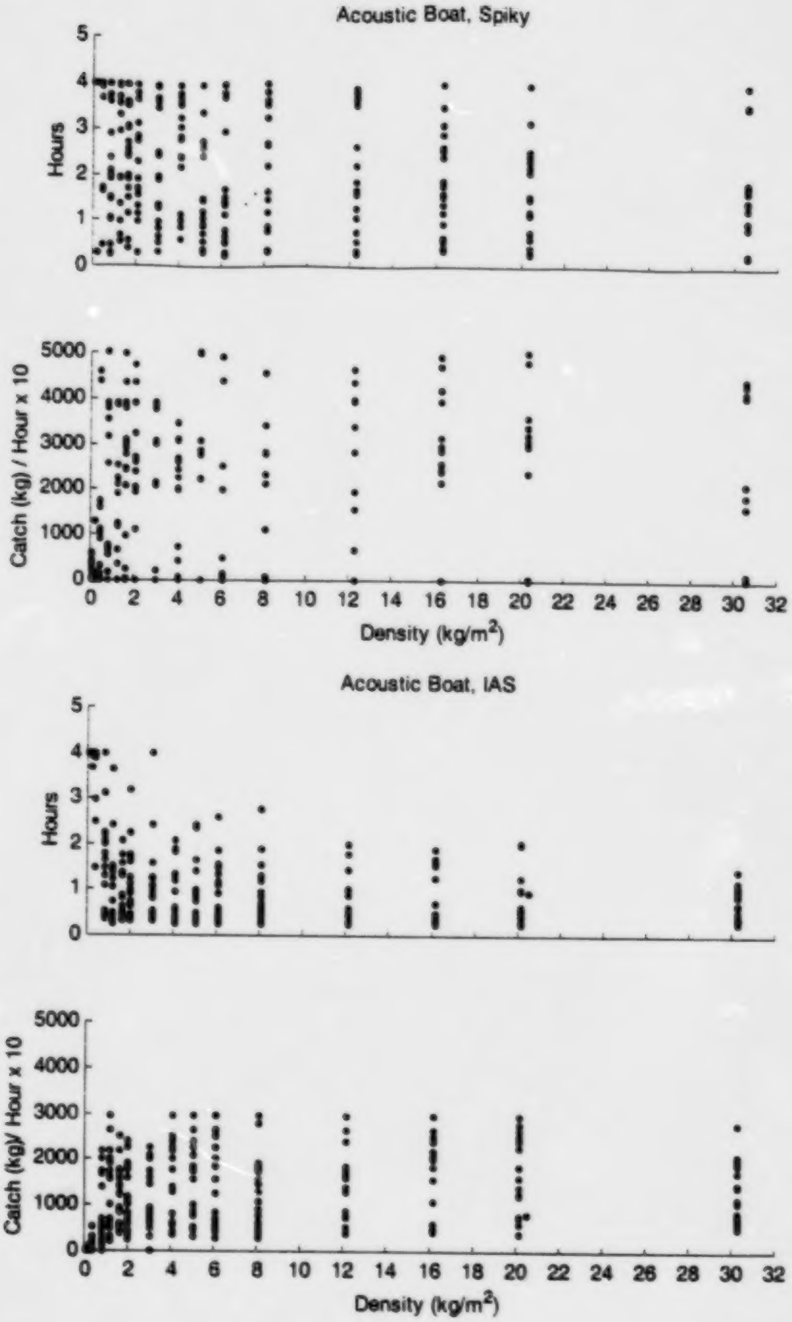

Acoustic Boat, Spiky
Hours
0
1
2
3
4
5
Catch (kg) / Hour x 10
0
1000
2000
3000
4000
5000
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32
Density (kg/m²)
Acoustic Boat, IAS
Hours
0
1
2
3
4
5
Catch (kg)/ Hour x 10
0
1000
2000
3000
4000
5000
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32
Density (kg/m²)

Fig. 61 (cont.).

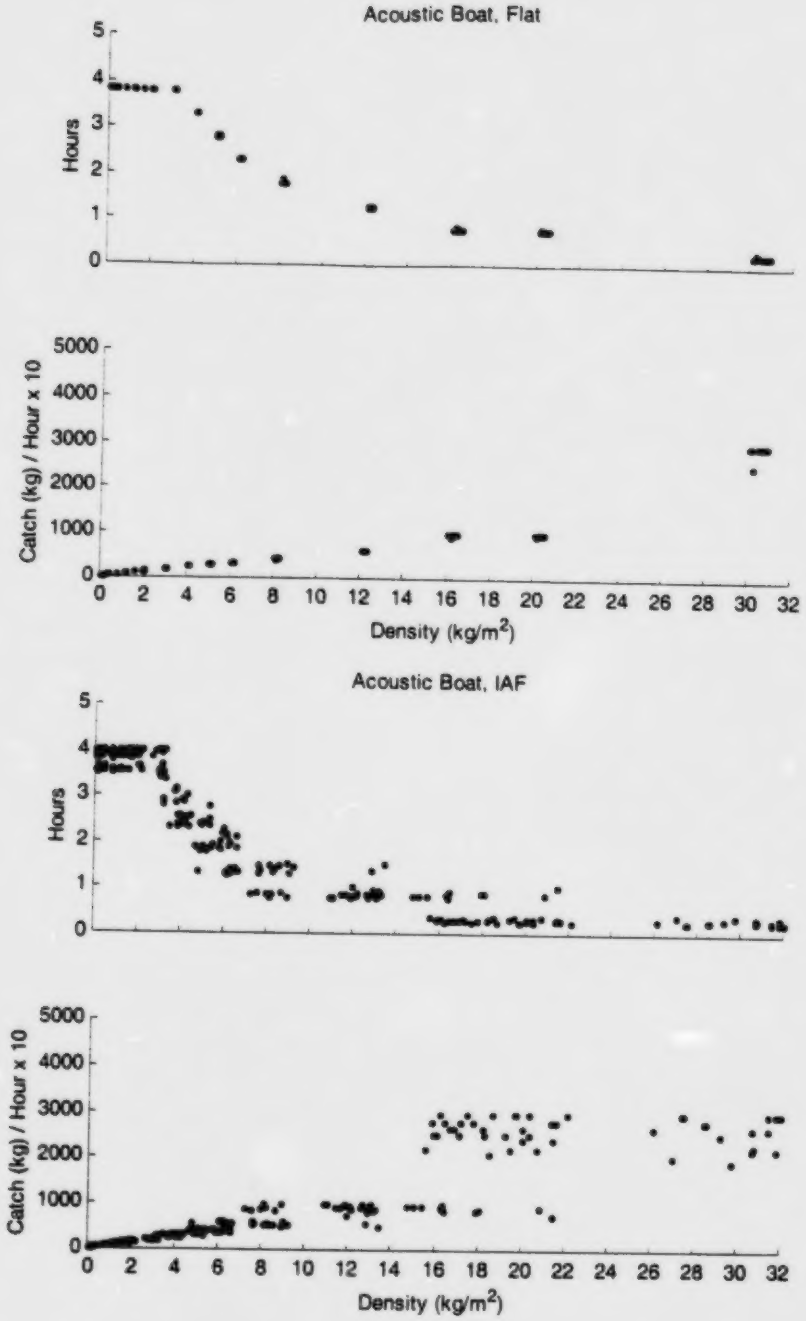

Acoustic Boat, Flat
Hours
0
1
2
3
4
5
Catch (kg) / Hour x 10
0
1000
2000
3000
4000
5000
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
Density (kg/m²)
Acoustic Boat, IAF
Hours
0
1
2
3
4
5
Catch (kg) / Hour x 10
0
1000
2000
3000
4000
5000
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
Density (kg/m²)

Fig. 61 (cont.).

6.20 Simulated index comparison

Plots of estimated biomass against true biomass indicate that variance in estimated biomass increases as true stock size increases for all distributions in the Movement - Fishing condition (Fig. 62). Except for the flat distribution, the arithmetic index always over-estimates true biomass (slope > 1). The fishing index usually underestimates biomass except for the spiky distributions (Fig. 62). The highest variances generally occur with the random tow surveys (Fig. 62). The searching, random tow, random transect, and systematic transect methods consistently give biomass estimates that appear close to the true values (Fig. 62).

Regression analysis on a case by case basis by survey type, distribution, fishing, and movement condition indicate that the standard error of the regression slope (sse) is < 0.10 for all regressions except those with the spiky distribution (Tables 11-14). All regressions were significant ($p < 0.0001$) (Tables 11-14). The low sse's indicate that there will likely not be any differences in interpretation between these unweighted regressions and weighted regressions between the true and estimated biomass.

For all conditions, the arithmetic index had the widest range in slopes between estimated and true biomass, followed by Searching - Fishing (Figs. 63-66). Random tow indices had the highest standard deviations for spiky distributions. Spiky distributions generally had the highest standard deviations, followed by IAS (Figs. 63-66). The Searching - Total, random tow, random transect, and systematic transect indices generally had slopes between the estimated and true biomass of between 0.5 - 1.5 (Figs. 63-66).

Overall, the survey methods random tow, random transect, and systematic transect had slopes between the true and estimated biomass that were closest to zero. Searching - Total slopes were higher for spiky compared to flat distributions. Slopes for spiky, IAS, and average distributions were close to zero (Fig. 67). There was least variation in slopes with the random transects index (Fig. 67).

Of the four methods most practical to use in forming an abundance index in this situation, random transects and systematic transects were proportional across all conditions. The Searching - Fishing index was not proportional across all conditions. The Searching - Total was in between the survey methods and the Searching - Fishing index in meeting the goal of displaying a proportional response to the density, across distribution and condition patterns (Fig. 68).

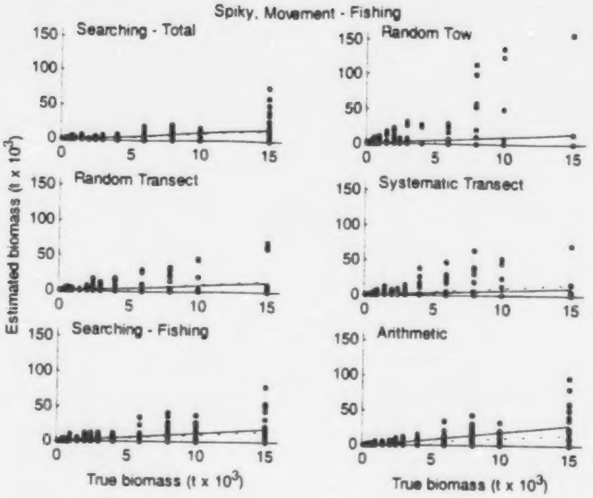


Fig. 62. The relationship between the true and the estimated biomass for the Movement - Fishing condition for all simulated distributions and survey types. Dotted line is true biomass and solid line is estimated biomass.

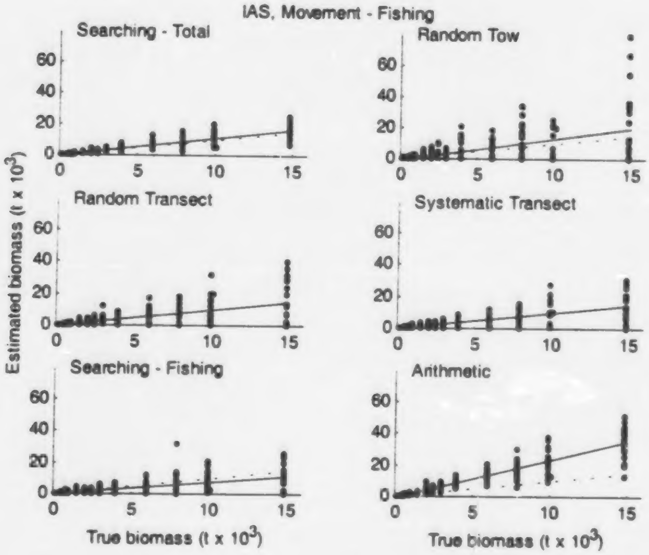


Fig. 62 (cont.).

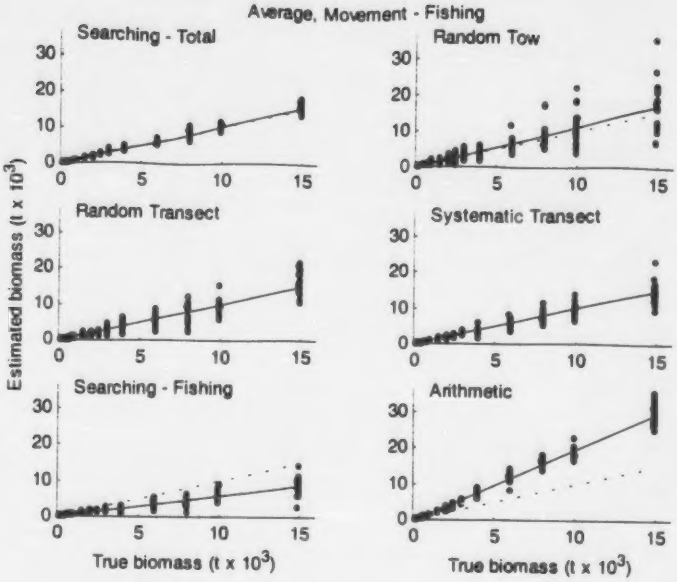


Fig. 62 (cont.).

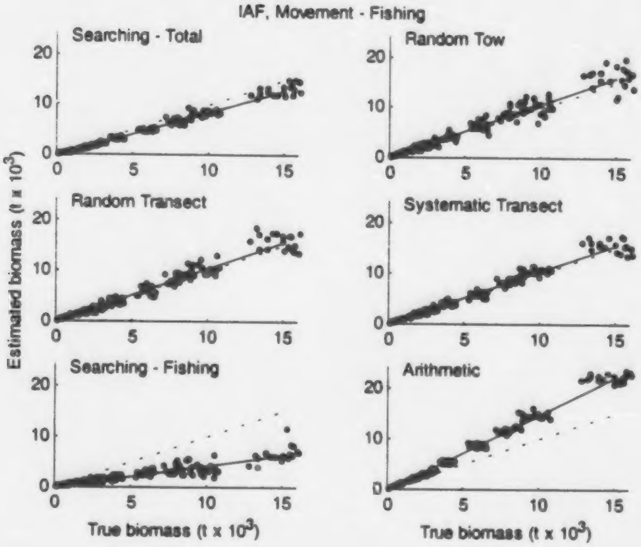


Fig. 62 (cont.).

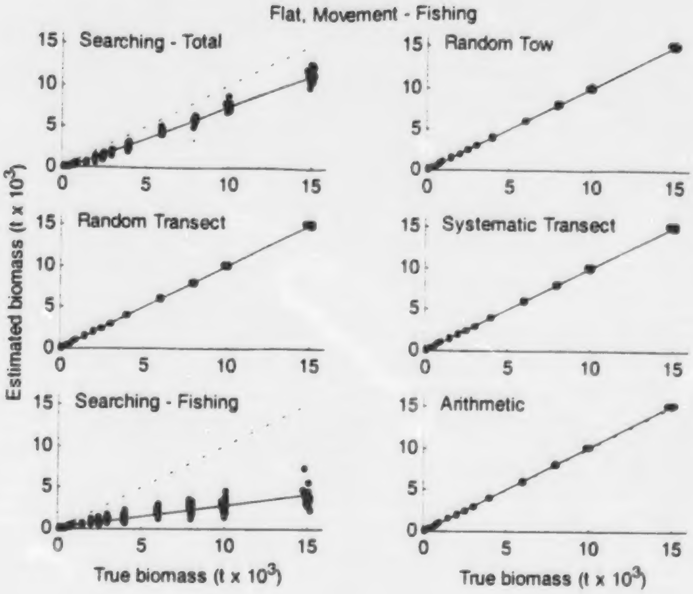

Flat, Movement - Fishing
Searching - Total
Random Tow
Random Transect
Systematic Transect
Searching - Fishing
Arithmetic
Estimated biomass (t x 10^3)
True biomass (t x 10^3)
True biomass (t x 10^3)
0
5
10
15

Fig. 62 (cont.).

Table 11. Parameter estimates for regression analysis of estimated biomass against true biomass for Movement - Fishing Condition and all simulated distributions and survey types. Sse, standard error of the regression slope. Sse values above 0.10 are bold. Search – T, Search – Total; Ran Tow, Random Tow; Ran Tran, Random Transect; Sys Tran, Systematic Transect; Search – F, Searching – Fishing.

Movement - Fishing

							Intercept	
Survey Type	Distribution	Sse	R^2	p-value	Slope	Intercept	Lower CI	Upper CI
Search -T	Spiky	0.09	0.39	0	1.25	-0.84	-1.77	0.08
Search -T	InterAveSpiky	0.03	0.86	0	1.14	-0.26	-0.53	0.02
Search -T	Average	0.01	0.99	0	1.06	-0.22	-0.30	-0.14
Search -T	InterAveFlat	0.01	0.99	0	0.86	-0.23	-0.29	-0.17
Search -T	Flat	0.00	0.99	0	0.78	-0.30	-0.35	-0.25
Ran Tow	Spiky	**0.23**	0.06	0	1.05	0.22	-2.16	2.61
Ran Tow	InterAveSpiky	0.10	0.39	0	1.40	-0.82	-1.85	0.21
Ran Tow	Average	0.03	0.81	0	1.15	-0.24	-0.57	0.09
Ran Tow	InterAveFlat	0.01	0.96	0	1.06	-0.03	-0.16	0.11
Ran Tow	Flat	0.00	1.00	0	1.00	-0.01	-0.01	0.00
Ran Tran	Spiky	**0.12**	0.15	0	0.91	-0.21	-1.47	1.05
Ran Tran	InterAveSpiky	0.06	0.47	0	0.99	-0.18	-0.80	0.44
Ran Tran	Average	0.02	0.90	0	1.02	-0.17	-0.37	0.02
Ran Tran	InterAveFlat	0.01	0.97	0	1.05	-0.10	-0.20	0.00
Ran Tran	Flat	0.00	1.00	0	1.00	-0.01	-0.02	0.00
Sys Tran	Spiky	**0.12**	0.07	0	0.58	0.85	-0.38	2.08
Sys Tran	InterAveSpiky	0.05	0.58	0	0.97	-0.24	-0.73	0.24
Sys Tran	Average	0.01	0.95	0	1.00	-0.14	-0.28	0.00
Sys Tran	InterAveFlat	0.01	0.98	0	1.04	-0.07	-0.16	0.01
Sys Tran	Flat	0.00	1.00	0	1.00	-0.01	-0.02	0.00
Search - F	Spiky	0.10	0.31	0	1.24	-0.30	-1.39	0.80
Search - F	InterAveSpiky	0.05	0.44	0	0.74	0.08	-0.41	0.57
Search - F	Average	0.01	0.88	0	0.58	0.05	-0.08	0.17
Search - F	InterAveFlat	0.01	0.89	0	0.41	0.10	0.02	0.18
Search - F	Flat	0.01	0.88	0	0.27	0.15	0.09	0.21
Arithmetic	Spiky	**0.12**	0.48	0	2.02	-1.31	-2.55	-0.07
Arithmetic	InterAveSpiky	0.05	0.87	0	2.38	-0.76	-1.30	-0.22
Arithmetic	Average	0.01	0.99	0	2.02	-0.49	-0.64	-0.35
Arithmetic	InterAveFlat	0.01	0.99	0	1.49	-0.31	-0.40	-0.22
Arithmetic	Flat	0.00	1.00	0	1.01	-0.01	-0.02	0.00

Table 12. Parameter estimates for regression analysis of estimated biomass against true biomass for No Movement - Fishing Condition and all simulated distributions and survey types. Sse, standard error of the regression slope. Sse values above 0.10 are bold. Search – T, Search – Total; Ran Tow, Random Tow; Ran Tran, Random Transect; Sys Tran, Systematic Transect; Search – F, Searching – Fishing.

No Movement - Fishing

							Intercept	
Survey Type	Distribution	Sse	R^2	p-value	Slope	Intercept	Lower CI	Upper CI
Search -T	Spiky	0.04	0.54	0.00	0.71	-0.13	-0.52	0.26
Search -T	InterAveSpiky	0.01	0.95	0.00	0.94	-0.23	-0.35	-0.11
Search -T	Average	0.00	1.00	0.00	0.97	-0.24	-0.28	-0.20
Search -T	InterAveFlat	0.00	0.99	0.00	0.78	-0.20	-0.24	-0.16
Search -T	Flat	0.01	0.98	0.00	0.74	-0.27	-0.33	-0.21
Ran Tow	Spiky	**0.20**	0.06	0.00	0.93	0.79	-1.37	2.94
Ran Tow	InterAveSpiky	0.08	0.28	0.00	0.91	0.26	-0.60	1.11
Ran Tow	Average	0.03	0.81	0.00	0.99	0.01	-0.28	0.29
Ran Tow	InterAveFlat	0.01	0.96	0.00	1.05	-0.09	-0.21	0.04
Ran Tow	Flat	0.00	1.00	0.00	1.00	0.00	-0.01	0.00
Ran Tran	Spiky	**0.12**	0.15	0.00	0.91	-0.28	-1.59	1.04
Ran Tran	InterAveSpiky	0.06	0.52	0.00	1.05	-0.36	-0.95	0.23
Ran Tran	Average	0.02	0.92	0.00	1.01	-0.15	-0.33	0.03
Ran Tran	InterAveFlat	0.01	0.98	0.00	1.00	-0.10	-0.19	-0.01
Ran Tran	Flat	0.00	1.00	0.00	1.00	-0.01	-0.01	0.00
Sys Tran	Spiky	0.10	0.23	0.00	1.03	-0.95	-2.06	0.16
Sys Tran	InterAveSpiky	0.03	0.75	0.00	0.91	0.05	-0.25	0.36
Sys Tran	Average	0.00	1.00	0.00	0.99	-0.13	-0.14	-0.11
Sys Tran	InterAveFlat	0.00	1.00	0.00	0.99	-0.07	-0.08	-0.06
Sys Tran	Flat	0.00	1.00	0.00	1.00	0.00	-0.01	0.00
Search - F	Spiky	**0.11**	0.25	0.00	1.10	-0.19	-1.31	0.93
Search - F	InterAveSpiky	0.05	0.35	0.00	0.62	0.12	-0.38	0.62
Search - F	Average	0.01	0.79	0.00	0.46	0.16	0.02	0.30
Search - F	InterAveFlat	0.01	0.90	0.00	0.37	0.16	0.09	0.23
Search - F	Flat	0.01	0.88	0.00	0.28	0.14	0.07	0.20
Arithmetic	Spiky	**0.12**	0.48	0.00	2.13	-0.92	-2.23	0.40
Arithmetic	InterAveSpiky	0.05	0.90	0.00	2.52	-0.75	-1.25	-0.24
Arithmetic	Average	0.02	0.96	0.00	1.85	-0.47	-0.69	-0.25
Arithmetic	InterAveFlat	0.01	0.99	0.00	1.44	-0.30	-0.37	-0.24
Arithmetic	Flat	0.00	1.00	0.00	1.01	-0.01	-0.02	-0.01

Table 13. Parameter estimates for regression analysis of estimated biomass against true biomass for Movement - No Fishing Condition and all simulated distributions and survey types. Sse, standard error of the regression slope. Sse values above 0.10 are bold. Search – T, Search – Total; Ran Tow, Random Tow; Ran Tran, Random Transect; Sys Tran, Systematic Transect.

Movement - No Fishing

							Intercept	
Survey Type	Distribution	Sse	R^2	p-value	Slope	Intercept	Lower CI	Upper CI
Search -T	Spiky	0.07	0.58	0.00	1.44	-0.61	-1.34	0.12
Search -T	InterAveSpiky	0.02	0.89	0.00	1.17	-0.03	-0.27	0.21
Search -T	Average	0.01	0.99	0.00	1.09	0.02	-0.05	0.09
Search -T	InterAveFlat	0.01	0.99	0.00	0.86	0.09	0.03	0.14
Search -T	Flat	0.00	0.99	0.00	0.77	0.01	-0.03	0.05
Ran Tow	Spiky	**0.28**	0.06	0.00	1.30	-0.25	-3.26	2.77
Ran Tow	InterAveSpiky	0.09	0.21	0.00	0.81	0.62	-0.30	1.53
Ran Tow	Average	0.03	0.79	0.00	1.07	0.13	-0.20	0.45
Ran Tow	InterAveFlat	0.01	0.96	0.00	1.09	0.00	-0.14	0.13
Ran Tow	Flat	0.00	1.00	0.00	1.00	0.00	-0.01	0.01
Ran Tran	Spiky	**0.14**	0.10	0.00	0.81	0.91	-0.56	2.37
Ran Tran	InterAveSpiky	0.05	0.43	0.00	0.86	0.30	-0.27	0.88
Ran Tran	Average	0.02	0.89	0.00	1.00	0.04	-0.17	0.24
Ran Tran	InterAveFlat	0.01	0.96	0.00	0.98	0.06	-0.06	0.18
Ran Tran	Flat	0.00	1.00	0.00	1.00	-0.01	-0.01	0.00
Sys Tran	Spiky	**0.13**	0.15	0.00	1.01	0.40	-1.00	1.80
Sys Tran	InterAveSpiky	0.06	0.56	0.00	1.14	-0.21	-0.80	0.37
Sys Tran	Average	0.01	0.94	0.00	1.00	-0.01	-0.16	0.14
Sys Tran	InterAveFlat	0.01	0.98	0.00	1.04	-0.01	-0.09	0.07
Sys Tran	Flat	0.00	1.00	0.00	1.00	0.00	-0.01	0.00
Arithmetic	Spiky	0.09	0.69	0.00	2.49	-0.62	-1.61	0.37
Arithmetic	InterAveSpiky	0.05	0.91	0.00	2.64	-0.51	-0.99	-0.03
Arithmetic	Average	0.01	0.99	0.00	2.08	-0.06	-0.19	0.07
Arithmetic	InterAveFlat	0.01	1.00	0.00	1.53	-0.16	-0.23	-0.10
Arithmetic	Flat	0.00	1.00	0.00	1.02	0.00	-0.01	0.00

Table 14. Parameter estimates for regression analysis of estimated biomass against true biomass for No Movement - No Fishing Condition and all simulated distributions and survey types. Sse, standard error of the regression slope. Sse values above 0.10 are bold. Search – T, Search – Total; Ran Tow, Random Tow; Ran Tran, Random Transect; Sys Tran, Systematic Transect.

No Movement - No Fishing

							Intercept	
Survey Type	Distribution	Sse	R^2	p-value	Slope	Intercept	Lower CI	Upper CI
Search -T	Spiky	0.04	0.65	0.00	1.03	-0.28	-0.73	0.17
Search -T	InterAveSpiky	0.01	0.96	0.00	0.98	0.00	-0.12	0.12
Search -T	Average	0.00	0.99	0.00	0.97	0.03	-0.02	0.07
Search -T	InterAveFlat	0.00	1.00	0.00	0.79	0.07	0.04	0.11
Search -T	Flat	0.00	0.99	0.00	0.74	0.02	-0.03	0.06
Ran Tow	Spiky	**0.25**	0.06	0.00	1.14	0.38	-2.30	3.06
Ran Tow	InterAveSpiky	0.09	0.27	0.00	1.01	0.27	-0.71	1.25
Ran Tow	Average	0.02	0.86	0.00	1.10	0.06	-0.19	0.32
Ran Tow	InterAveFlat	0.01	0.97	0.00	1.08	-0.05	-0.16	0.07
Ran Tow	Flat	0.00	1.00	0.00	1.00	0.00	-0.01	0.00
Ran Tran	Spiky	**0.15**	0.09	0.00	0.83	0.15	-1.46	1.75
Ran Tran	InterAveSpiky	0.06	0.57	0.00	1.24	-0.41	-1.05	0.23
Ran Tran	Average	0.02	0.92	0.00	0.99	0.02	-0.15	0.20
Ran Tran	InterAveFlat	0.01	0.99	0.00	0.99	0.02	-0.05	0.09
Ran Tran	Flat	0.00	1.00	0.00	1.00	0.00	0.00	0.01
Sys Tran	Spiky	**0.13**	0.27	0.00	1.37	-0.53	-1.88	0.83
Sys Tran	InterAveSpiky	0.03	0.77	0.00	1.00	0.12	-0.20	0.44
Sys Tran	Average	0.00	1.00	0.00	1.00	0.00	0.00	0.00
Sys Tran	InterAveFlat	0.00	1.00	0.00	1.00	0.00	0.00	0.00
Sys Tran	Flat	0.00	1.00	0.00	1.00	0.00	0.00	0.00
Arithmetic	Spiky	0.10	0.64	0.00	2.47	-0.17	-1.27	0.93
Arithmetic	InterAveSpiky	0.05	0.90	0.00	2.78	-0.26	-0.81	0.29
Arithmetic	Average	0.02	0.96	0.00	1.96	0.13	-0.11	0.37
Arithmetic	InterAveFlat	0.01	1.00	0.00	1.47	-0.16	-0.22	-0.10
Arithmetic	Flat	0.00	1.00	0.00	1.02	0.00	-0.01	0.00

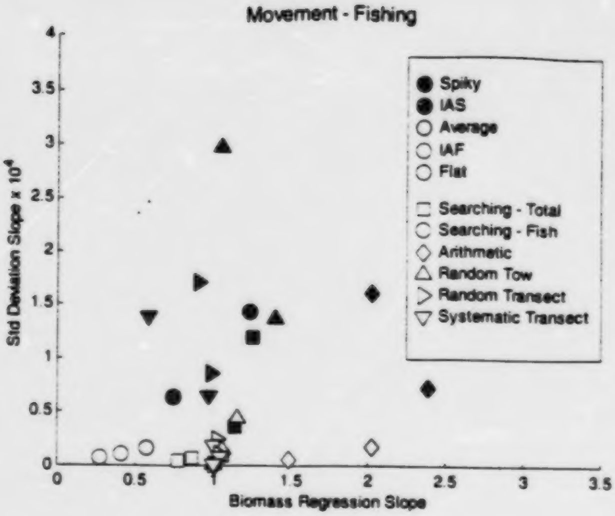


Fig. 63. A summary of the relationship between the true and the estimated biomass for the Movement - Fishing condition and all simulated distributions and survey types. The standard deviation of the biomass estimates are plotted against the slope of the regression for each distribution. Gray shading represents the distribution types and symbols represent the survey types. Axes for Figs. 63–66 are constant to allow comparison among the movement and fishing conditions.

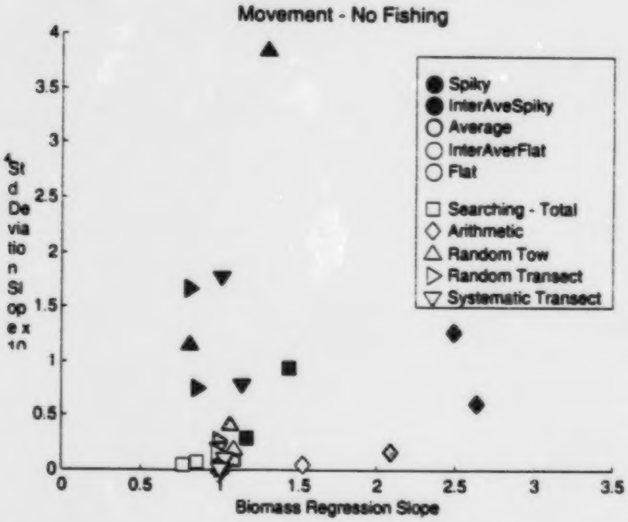


Fig. 64. A summary of the relationship between the true and the estimated biomass for the Movement - No Fishing condition and all simulated distributions and survey types. The standard deviation of the biomass estimates are plotted against the slope of the regression for each distribution. Gray shading represents the distribution types and symbols represent the survey types. Axes for Figs. 63–66 are constant to allow comparison among the movement and fishing conditions.

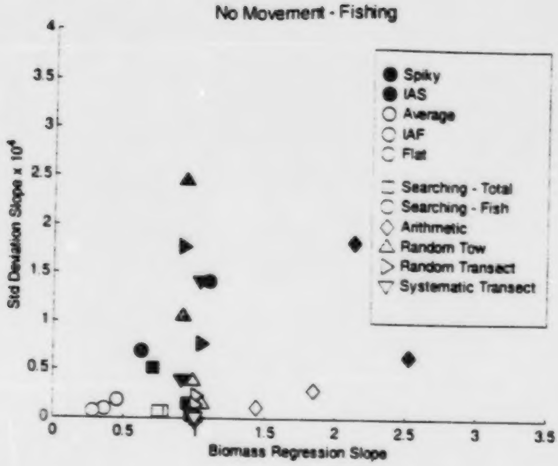


Fig. 65. A summary of the relationship between the true and the estimated biomass for the No Movement - Fishing condition and all simulated distributions and survey types. The standard deviation of the biomass estimates are plotted against the slope of the regression for each distribution. Gray shading represents the distribution types and symbols represent the survey types. Axes for Figs. 63–66 are constant to allow comparison among the movement and fishing conditions.

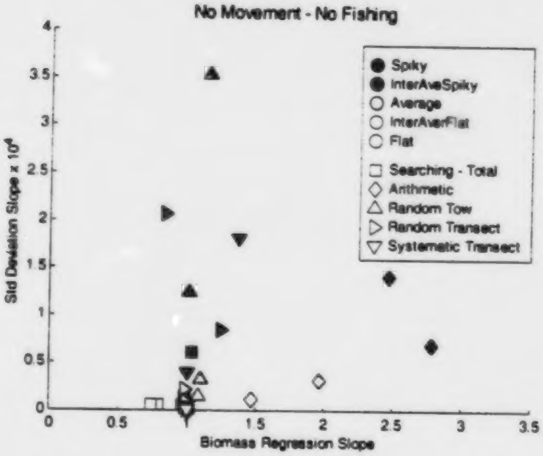


Fig. 66. A summary of the relationship between the true and the estimated biomass for the No Movement - No Fishing condition and all simulated distributions and survey types. The standard deviation of the biomass estimates are plotted against the slope of the regression for each distribution. Gray shading represents the distribution types and symbols represent the survey types. Axes for Figs. 63–66 are constant to allow comparison among the movement and fishing conditions.

6.21 Total allowable catch - TAC

Evaluation by the TAC method indicates that average simulated exploitation rates are usually within 10% of the target using the Searching – Total biomass estimate for the spiky distribution. For the other distributions the simulated Searching – Total biomass estimates were similar to the target but well under the target for flat distributions. In contrast, the arithmetic biomass estimates produced exploitation rates that were usually above the target, while the Searching – Fishing index gave results that were usually below the target (Fig. 69).

Simulated survey indices usually produced average exploitation rates that were similar to the target, except for the spiky distribution where they performed worse than the searching indices (Fig. 69).

The percentage of cases with exploitation rates > 40% were greatest for the spiky distribution for Searching and Survey biomass estimates. The arithmetic and Searching - Fishing biomass estimates generally had percentages > 40% and were higher than those for Searching – Total. Arithmetic biomass estimates always produced the highest exploitation rates regardless of distribution.

Percentages of exploitation rates > 40% were similar to Searching – Total for all survey indices at the spiky distribution. For IAS and Average distributions, the Searching indices had lower percentages > 40% than the survey indices (Fig. 70). Flat and IAF distributions had no cases > 40% for any index method.

6.22 Exploitation rates and the importance of distribution

High exploitation rates occurred at low densities for spiky and IAS simulated distributions and decreased as density increased. For the other simulated distributions, exploitation rate peaked for densities in the range of 2 to 4 kg/m^2, then declined as density increased (Fig. 71).

Distribution type was a good predictor of mean variance in density regardless of fishing and movement condition (Fig. 72).

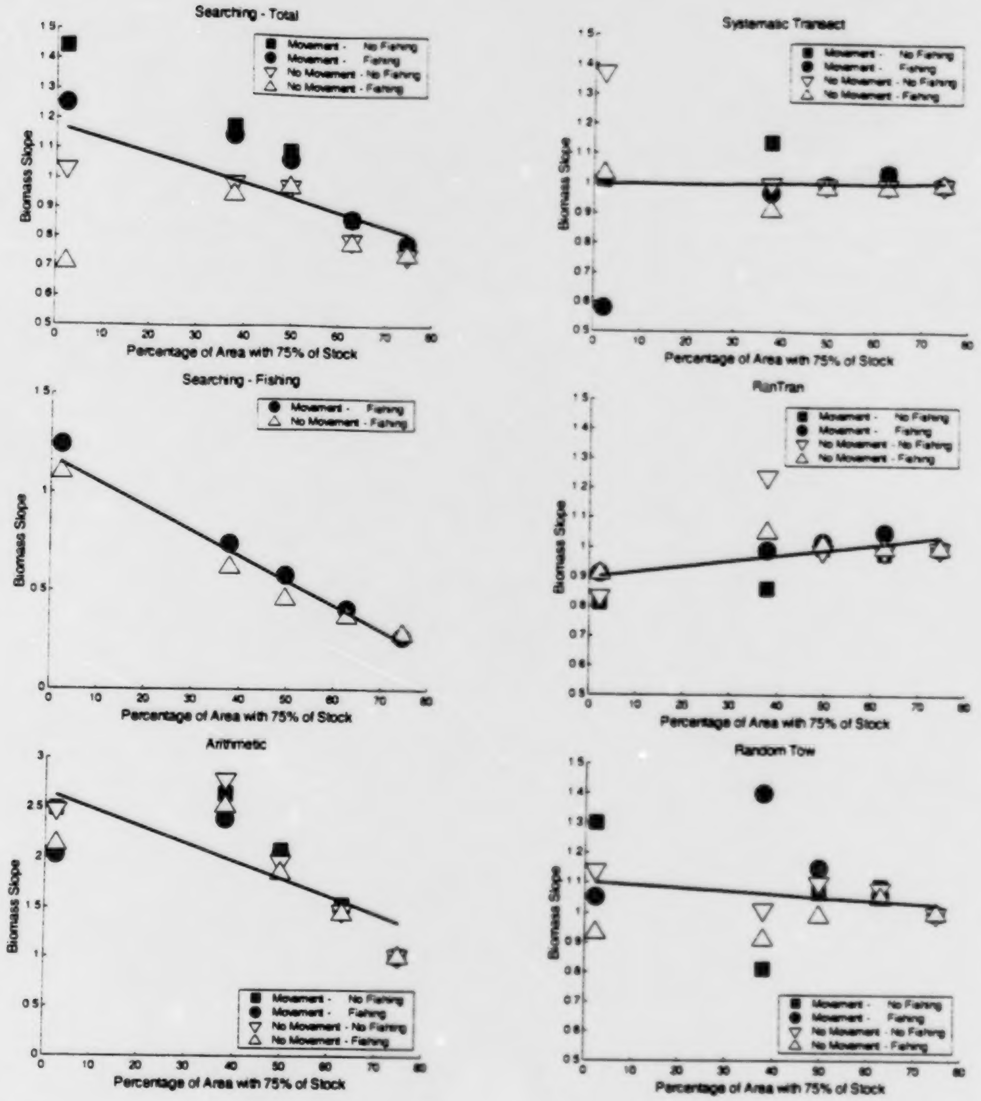


Fig. 67. The relationship between the estimated and the true biomass regression slope and the percentage of the area with 75% of the stock for each distribution and all Movement - Fishing conditions. Scales are identical for Searching – Total and three survey methods but differ for Searching – Fishing and Arithmetic methods.

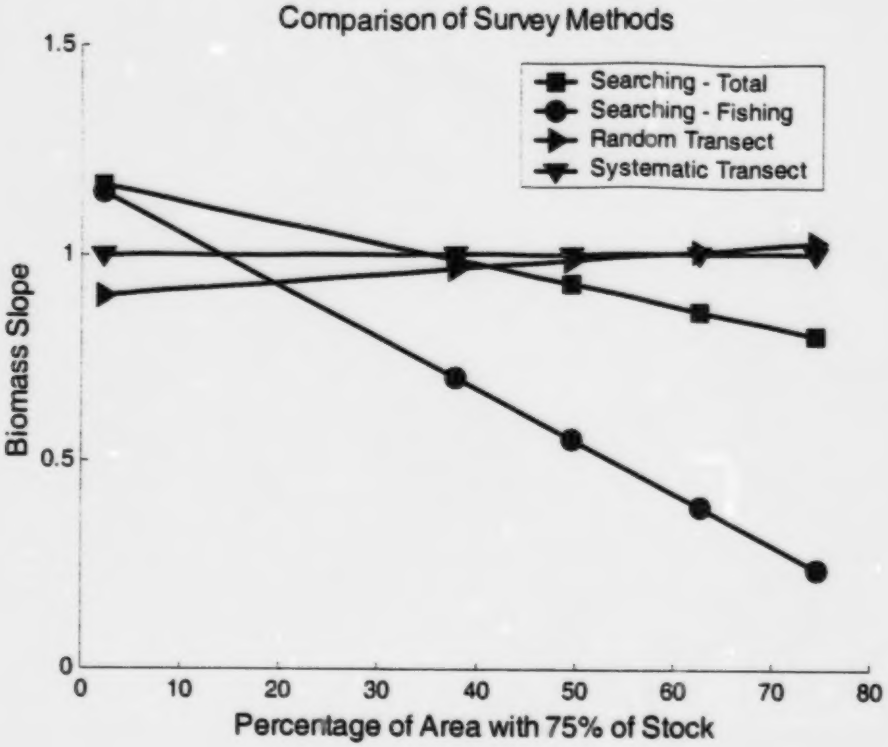


Fig. 68. The relationship between the slopes between the estimated and the true biomass and the percentage of the area with 75% of the stock for each distribution for key survey types with all conditions combined. As the x-axis increases in percentage of area with 75% of the stock the distribution becomes more flat.

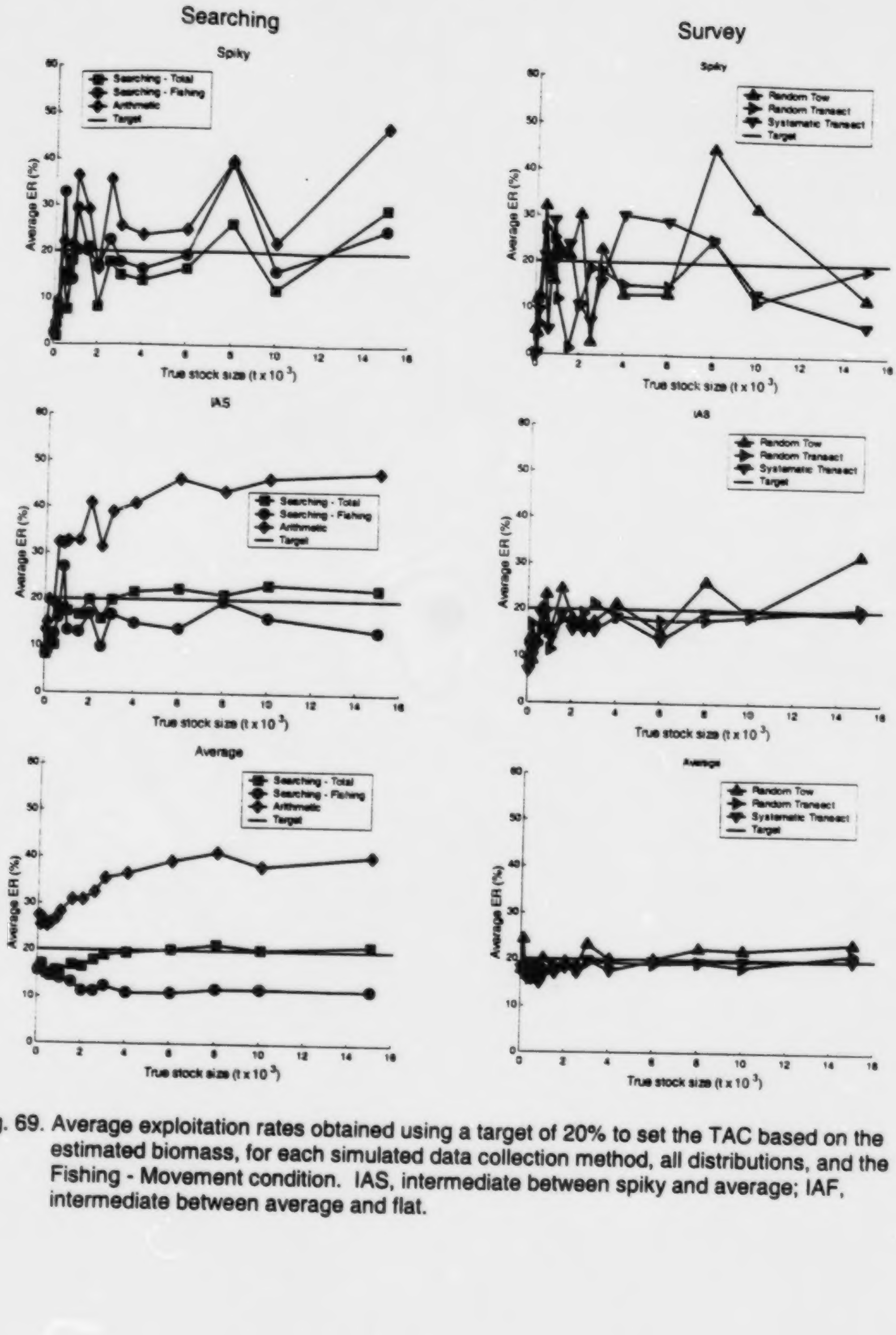


Fig. 69. Average exploitation rates obtained using a target of 20% to set the TAC based on the estimated biomass, for each simulated data collection method, all distributions, and the Fishing - Movement condition. IAS, intermediate between spiky and average; IAF, intermediate between average and flat.

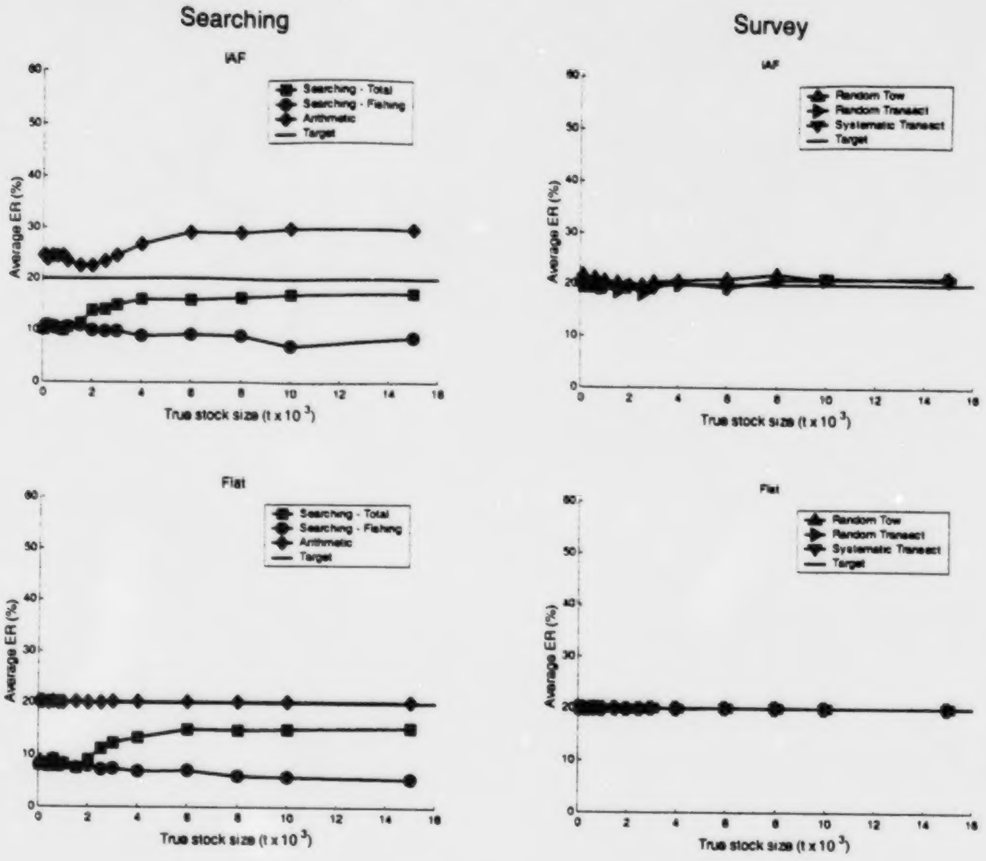

Searching
Survey
IAF
Searching - Total
Searching - Fishing
Arithmetic
Target
Random Tow
Random Transect
Systematic Transect
Target
Flat
Average ER (%)
True stock size (t x 10 3)
0
10
20
30
40
50
60
2
4
6
8
10
12
14
16

Fig. 69. (cont.)

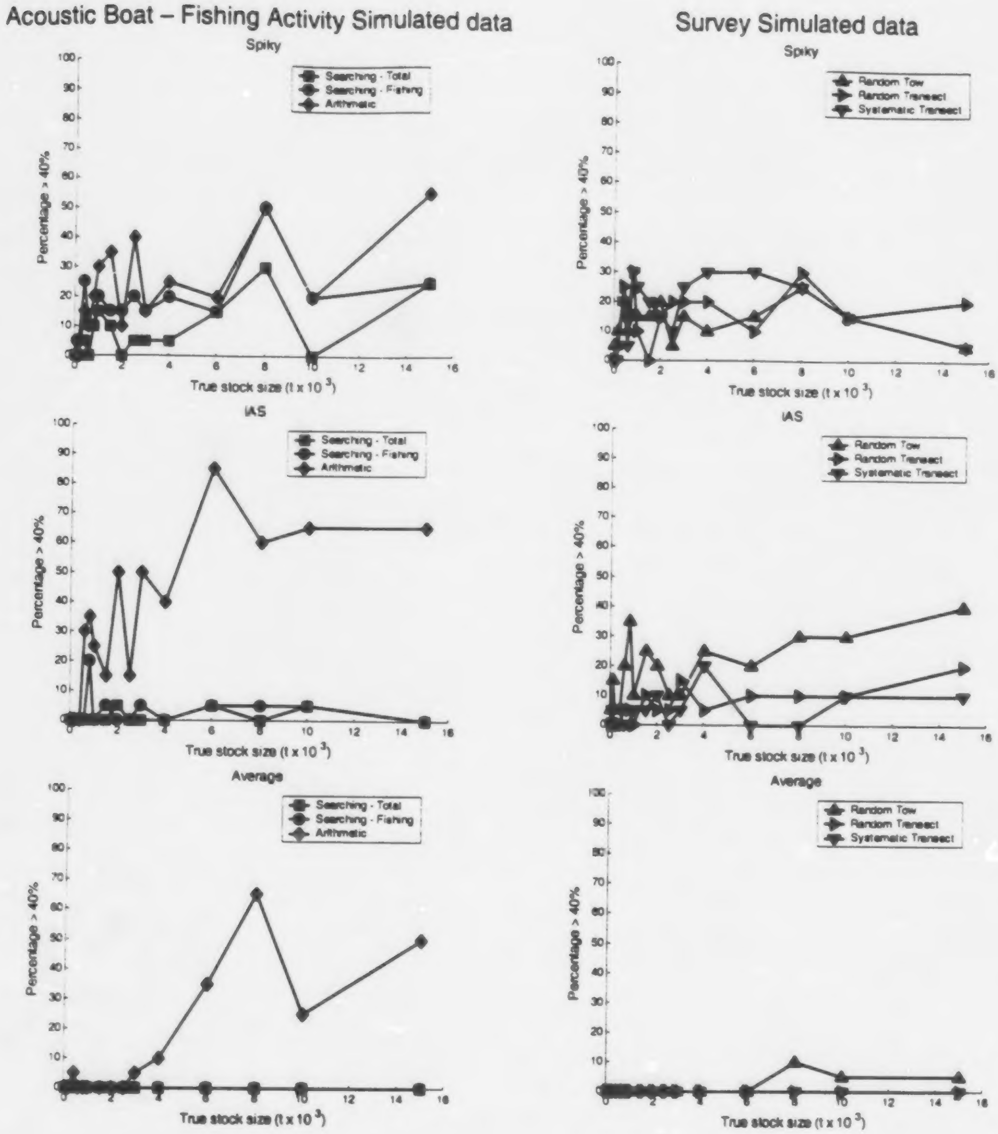


Fig. 70. Trends in the percentage of exploitation rates that were over 40% or double the target for each simulated data collection method on each distribution, as a function of biomass. Percentages for InterAveFlat (IAF) and Flat were all zero and are not shown. IAS, intermediate between spiky and average.

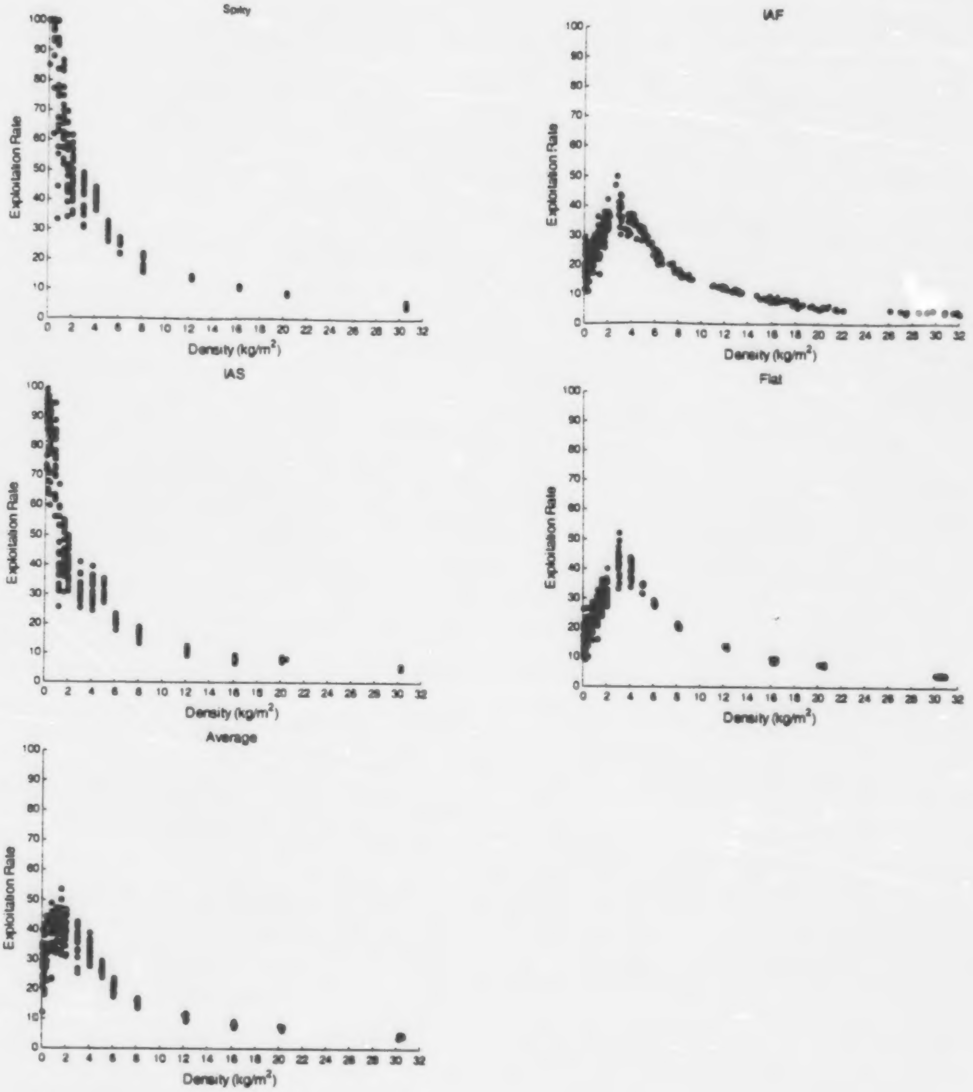


Fig. 71. Examples of the average exploitation rates found in closed loop simulations of Movement - Fishing conditions and all distributions, as functions of stock density. IAS, intermediate between spiky and average; IAF, intermediate between average and flat.

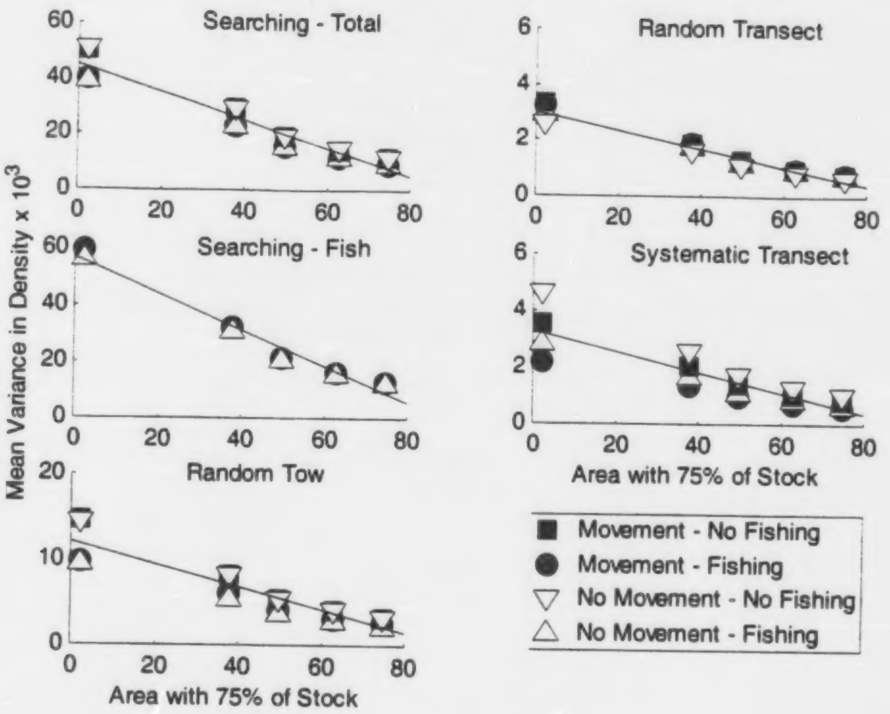


Fig. 72. Mean variance in density for each simulated data collection method and each distribution. Gray shading and symbols refer to fishing - movement conditions.

6.23 Discussion - Simulation model validation

The objective of the simulation study was to create a model that was compatible with known characteristics of fish and fishing fleet behaviour in a small inshore gillnet fishery. Compatibility was important in order to make conclusions about the properties and expectations of various stock indices that could be collected on herring spawning aggregations. Of particular interest were the properties of the Searching - Total and Searching - Fishing indices because they could represent effective alternatives to traditional survey designs in deriving stock biomass trend indices.

The distributions examined cover the range of those observed in the Pictou 1997 fishery (compare Figs. 39, 40, 41). The 29 September 1997 data set is an example of a spiky distribution from the fishery (Fig. 41), while 26 September is an example of an intermediate between average and spiky distribution (IAS), 07 September is an average distribution, and 09 September 1997 is an example of an intermediate between average and flat distribution (IAF) (Fig. 41). There were no flat distributions with densities high enough to attract searching behaviour in the 1997 Pictou fishery. The two-dimensional contours generated from the Pictou fishery data show more structure than the simulated data (compare Figs. 42, 43). One reason for this difference is that the contours from the fishery data depend only on the data collected, while those drawn from the simulation use an evenly spaced grid. These comparisons demonstrate that the model spans the extreme distributions expected in the fishery and also represents the intermediate distributions.

Very little is known about the movement patterns of herring schools on an hourly basis during a fishery. Nevertheless, it is safe to assume fishing activity would cause some fish movement. The objective of simulating fish movement in the population was to create a pattern that would represent rapid movement of fish, and one that would maximally disrupt the proportionality criterion with respect to the searching and survey methods. The two examples provided (compare Figs. 44, 45) indicate that the simulation provided rapidly changing distributions of fish schools in the area being searched and surveyed.

The data collection from the simulated searching and surveying methods and from the1997 Pictou fishery searching are far more intensive in terms of data points / m^2 than those found in typical trawl and acoustic surveys associated with this herring stock (compare Figs. 46-50 and Claytor and LeBlanc 1999). Even with this intensity, the peaks of the distributions are missed, particularly with the spiky distributions. Transect surveys, which are more likely to be used in this situation, are not as likely to miss these peaks (Figs. 46, 47). This difference explains the relatively higher variance in the estimated biomass using the random tow method compared to the transect and searching simulated data collection methods (Fig. 62).

The simulated fishery data captures the spatial trends expected from examinations of the 1997 Pictou fishery. Most of the fishing by the simulated fleet takes place on the peaks of the distribution, with a few individual boats displaced from those peaks (Fig. 51). The catch and catch rate patterns in the fleet and the acoustic boat are similar to those expected from the 1997 Pictou fishery (Figs. 54, 55). The effect of boat limits on total catches and catch rates is clearly demonstrated and the number of sets required to catch the boat limit declines as density increases (Figs. 54, 55). This compatibility between the simulation model and fishery is supported by the overall similarity between the simulated and the 1997 Pictou von Bertalanffy catch rate models (compare Tables 9, 10; Figs. 56-59). These results do, however, illustrate the differences that can occur depending on the distribution of the fish schools.

Catch / hour is an index that may provide a more stable index from the fishery than catch / net (Claytor and Clay 2001) (compare Figs. 29, 31, 32, 34, 55, 61). This simulation was not designed to study this effect but it indicates that this index might be useful at lower densities. However, at high densities an asymptote is reached (Fig. 61). In addition, catch / hour does not seem to be a suitable index for the spiky type of distributions (Fig. 61). The restriction to a four hour search limit may be influencing these results. This effect has not been investigated in this model and catch / metre searched is not considered as an alternative index in this thesis.

6.24 Discussion - Spatial analysis voronoi polygons

Voronoi polygons are a method not often encountered in biomass estimation of fish schools. Its primary use in ecology has been to describe spatial relationships such as territory distances that can be depicted as mosaics in plant and animal ecology (Pielou 1977). Byers (1992) describes the use of this technique to analyze attack patterns of bark beetles. Upton and Fingleton (1985) give other examples of their use in animal ecology, and Boots and Murdoch (1983) provide examples from the geosciences.

One feature of analysis using voronoi polygons is that a discrete surface is created, that is based on the influence of each simulated data point. That is, each simulated data point retains its true value and only has influence within its polygon. This feature has the affect of avoiding surface artifacts that result from models that assume smooth density variation when interpolating between points or are influenced by grid spacing (Fig. 53). This feature also allows anisotropic effects to be easily modeled (Gold and Roos 1994). Variograms for kriging were often difficult to fit to the data because of anisotropic effects (Figs. 25–27; Appendix 1) and sharp edges representing shoal boundaries.

It was desirable to use the convex hull to define the outer boundary of the voronoi polygons for two reasons. First, the outermost simulated data points would otherwise be eliminated from the analysis. Second, many of the outermost points would have an area of influence that was much larger than all the others, and those points would have undo influence on the estimated biomass index (Fig. 52).

6.25 Discussion - Comparison of fishery acoustic and survey indices

Proportionality was the principal factor testing performance of the proposed indices. The slope between estimated and true biomass need not always be one to be proportional and provide a good index. For example, suppose that the estimation method always under-estimated the true biomass by 80%, regardless of distribution. These estimates would provide a good index of biomass because the relationship with true biomass is linear and predictable regardless of distribution. As a result, when the slope for each distribution was plotted against the quantitative description of the distribution, in this case the area with 75% of the biomass, the result would be a regression slope of zero.

Using the criterion of proportionality between estimated and true biomass, with slope being equal to zero for all conditions and across all distributions, the three survey methods performed better than the search methods. Of the three simulated searching indices, only the Searching - Total index, can be considered as a candidate for a useful alternative to indices derived from surveys (Fig. 67). Slopes for each of the survey indices were generally near one when averaged across condition for each distribution (Fig. 67). The Searching - Total index averaged near one for spiky to average distributions but was < 1 for flatter distributions (Fig. 67).

Searching - Fishing generally had slopes that were < 1, indicating that it consistently under-estimated true biomass (compare Figs. 63-66). This result occurred because Searching - Fishing indices include smaller portions of the search area than Searching - Total. For example, simulated data collection was discontinued if the boat limit was caught before the four-hour search time was completed and as a result, it would cover a relatively small area (Fig. 53). This area would vary as the time to catch the boat limit varied. As a result, the slopes between Searching - Fishing estimated and true biomass were not proportional across the distributions (Fig. 67) and it was a poor index. The arithmetic index was always > 1 and had a greater variation in slopes across distributions and conditions than the other methods (Fig. 67). Neither the Searching - Fishing or Arithmetic indices would be a suitable index from this point of view.

Fish school distribution had a stronger effect on the relationship between the estimated and true biomass and the variance around this relationship than did movement or fishing condition within a survey type. Spiky type distributions led to the highest slopes between standard deviation and true biomass regardless of sampling method and simulation condition (compare Figs. 63-66). These slopes were always highest for the random tow collection, probably because this method had the fewest simulated data points associated with it and had a higher probability of missing the distribution than the other methods. The Searching - Total index always had lower standard deviations for the spiky distributions than did the survey methods (compare Figs. 63-66). Standard deviations were similar amongst methods for average to flat distributions (compare Figs. 63-66).

Survey methods on average produced better estimates of the true biomass (Fig. 68) but had greater variation around those estimates than using the Searching - Total index. The biggest differences in slopes for the Searching - Total index occurred between the extreme spiky and flat distributions. Incorporating the distribution type into the model may improve indices derived from the Searching - Total simulated data collection method.

The closed loop simulations assume that the relationship between the estimated biomass of each of the methods and the true biomass is perfectly understood. In terms of average exploitation rate relative to a target, this analysis indicates that there is little difference expected among the Searching - Total and three survey indices (Fig. 69). Variation of the survey indices, however, is greater compared to the Searching - Total index. This difference is indicated by the higher percentage of exploitation rates that would be double the target (Fig. 70). These higher exploitation rates imply that survey indices could be more risky to use as a basis for setting TACs than the Searching - Total indices.

These results indicate that knowing the distribution of the fish schools has a major influence on the expected exploitation rate. Exploitation rates were always higher and more variable at stock densities < 10 kg / m^2 than above this level with no other controls than boat limit (Fig. 71). Exploitation rates were always highest for spiky and IAS distributions (Fig. 71). Identifying the expected distribution type will be important for improving methods to control exploitation rates. The mean variance in density as measured by the Searching - Total index may be a way of identifying the distribution of the fish schools on any given night (Fig. 72). Incorporating this information into index formulation is an important area of future work.

These results indicate that, on average, survey indices will provide a more unbiased stock trend index than the Searching - Total index. There are, however, advantages that the Searching - Total index may have, including lower variance, bias, and risk of high exploitation rates. In addition, management actions may not be that different if indices and assessments are based on Searching - Total versus survey indices.

Searching - Total type indices will likely provide a useful tool for stock assessments for herring fisheries on local spawning aggregations of the type described by the simulation model. They could be improved by a better understanding of the relationship between distribution, variance, and abundance. A useful field comparison would include several nights of indices derived from simulated data collected from Searching - Total methods with either or both of the random transect and systematic simulated data.

7. Conclusion

The paradigm for the management of southern Gulf of St. Lawrence Atlantic herring has been a fixed exploitation rate strategy with $F_{0.1}$ as the reference point. The total allowable catch (TAC) has generally been set at the best estimate of $F_{0.1}$ for the entire spring or fall spawning stock. Inshore fleets associated with geographically defined spawning components are annually assigned proportions of the TAC. These proportions were established in the late 1980s. A six vessel purse seine fleet is allocated a fixed percentage of the overall TAC. This paradigm treats all of the herring populations within the southern Gulf of St. Lawrence as the basic management unit and has not been greatly modified since its implementation.

The indices derived from acoustic density estimates collected by fishing boats during regular fishing activity provide the opportunity to adopt an alternative management paradigm. The new paradigm would be based on decision rules that allow the metapopulation structure of Atlantic herring to become the basic management unit of this species. The decision rule paradigm does not depend on a fixed exploitation rate as its foundation, though it may use exploitation rates to define goals. In contrast, it is a paradigm that puts the emphasis on localized data collection in determining whether or not specific goals have been met, and serves as a basis for setting and changing the rules that govern a fishery. The elements of this paradigm have been described by Pearse and Walters (1992) and de la Mare (1998) and a form of these has been implemented in the 4Vn overwintering herring fishery in the southern Gulf of St. Lawrence (Figs. 2,3) herring fishery (Claytor 2000).

The abundance and exploitation rate indices derived from the acoustic data allow managers to directly measure the effects of decisions regarding when to fish and where to fish. Even without formal definition of these rules, it is clear that the gillnet exploitation rates which are 2 to 4 times the average should be avoided and could be prevented by shortening the season (Fig. 35).

One advantage of the decision rule approach is that the process becomes transparent to the fishing industry. In contrast to the current model which requires the use of population and statistical models to provide assessment advice, the decision rule paradigm utilizes the abundance and exploitation indices to make decisions regarding how to eliminate high exploitation rates and to take advantage of under-utilized fishing opportunities.

Another advantage of this approach is that it provides the fishing industry with the flexibility to collect data outside the fishing season, so as to determine the effects of the decision rules on the population. The Pictou, Nova Scotia group has conducted systematic surveys before and after the fishing season for this purpose. In 1997, pre-season surveys led to a fleet decision to delay the opening of the season by one week.

While indices derived from these data could be processed and made available for real time in-season management, such opportunities are limited within the southern Gulf of St. Lawrence because many of the fisheries occur simultaneously. A more realistic approach for this fishery would be to adopt rules for the fishing season, collect the data, and evaluate the performance of the decision rules as part of an annual stock assessment (Claytor 2000). In-season management by this method may be possible in areas where a single fleet sequentially harvests populations from various geographic areas. As a result, the approach is adaptive because feedback from the effects of the decision rules are used to alter those rules (Walters 1986).

The indices of spatial and temporal exploitation rates provided by the fishery collected acoustic data provide a foundation for establishing a management paradigm based on decision rules in the southern Gulf of St. Lawrence herring fishery. By providing a nightly measure of 'proven stock' (Pearce and Walters 1992) they furnish a method for investigating biological and management factors that lead to the feedback effects of the decision rules. Chief among these factors is likely to be the duration of exposure to the fishery.

The biology of herring likely has an appreciable effect on the exposure of herring to the southern Gulf of St. Lawrence fisheries. For example, Pacific herring (*Clupea harengus pallasi*) and Atlantic herring have both been observed to spawn in waves (Lambert 1987; Ware and Tanasichuk 1989). For Pacific herring, spawning waves of 5 - 6 days duration have been found with 8 - 26 days between waves (Ware and Tanasichuk 1989). For Atlantic herring, the duration of the waves, whether they occur, and their relationship to landings is uncertain. Some investigations have found older fish that spawn first (Lambert and Messieh 1989), while others have found that young fish spawn first (F. Mowbray, pers. comm. on unpublished data on Fisherman's Bank, PEI spawning bed surveys, Department of Fisheries and Oceans, P.O. Box 5030, Moncton, New Brunswick, Canada, E1C 9B6). Spawning bed surveys at Fisherman's Bank, Prince Edward Island have observed peaks in catches that are coincident with spawning events. However, there are also many examples of years in which catches follow the average pattern of peaks with no spawning occurring until after the season (Claytor et al. 1998b). The migration pattern and timing of herring on and off the spawning beds will affect calculations of exploitation rates over the entire season and will likely affect the implementation of decision rules designed to reduce overall exploitation rates. Similar migration and movement effects will likely alter decision rules concerning the purse seine fishery which harvests feeding and post-spawning herring.

One reason for the uncertainty surrounding spawning wave duration in Atlantic herring in the southern Gulf of St. Lawrence is that each of the cited studies has depended solely on fishery catch rate data to determine abundance of spawners in any given night. The acoustic data collection and analysis undertaken on the southern Gulf of St. Lawrence gillnet and purse seine fisheries provides a tool to investigate the density of spawning fish relative to spawning events that is not available using fishery catch rate or periodical survey data.

Other issues to explore with respect to the adoption of fishery acoustic indices as part of the management paradigm of Atlantic herring include: investigating inter-vessel consistency, examining the properties of the indices on a scale compatible with the purse seine fishery, and incorporating the properties of the fish distribution type and density variance into the index model. Adoption of a decision rule approach based on fishery acoustic indices would also alter the focus of assessment groups from one in which much of the emphasis on data collection is built around describing the age structure of the population, to one in which the emphasis is on the collection of acoustic data and fish length distributions.

The fishing industry does not speak in terms of metapopulations. However, they have implicitly adopted this view of the resource. They want fisheries controlled by the abundance of fish in their local areas independent of trends in other areas. The biggest impediment for managers of southern Gulf of St. Lawrence herring to change their current paradigm and adopt the metapopulation model is the lack of local abundance indices. Acoustic data collected by fishing fleets offers an opportunity to overcome this impediment and adopt a new management paradigm for these fisheries.

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Appendix 1. Details for kriging analysis showing variogram parameters and results of steps used to obtain biomass estimates by block kriging.

Table A1.1. Variogram parameters for data sets used to estimate biomass using block kriging.

					Omnidirectional Variograms	Anisotropic Variograms		Omnidirectional Rotated Variogram
Date	Region	Start Time	End Time	Parameter	Value	Value Angle 1	Value Angle 2	Value
Gillnet								
7-Sep	1	23.05	26.48	First Angle	0			
				Tolerance	90			
				Lag	30			
				No. of Lags	9			
				Range	123			
				Nugget	0.534			
				C1	0.455			
				Sill	0.989			
				Search Radius	250			
				Block Size	12.5			
7-Sep	1	29.01	30.93	First Angle	0			
				Tolerance	90			
				Lag	40			
				No. of Lags	6			
				Range	60			
				Nugget	0.61			
				C1	0.42			
				Sill	1.03			
				Search Radius	120			
				Block Size	12.5			
8-Sep	1	26.38	29.22	First Angle	0			
				Tolerance	90			
				Lag	50			
				No. of Lags	11			
				Range	460			
				Nugget	0.8			
				C1	0.29			
				Sill	1.09			
				Search Radius	920			
				Block Size	25			

Table A1.1. (cont).

Date	Region	Start Time	End Time	Parameter	Omnidirectional Variograms	Anisotropic Variograms		Omnidirectional Rotated Variogram
					Value	Value		Value
						Angle 1	Angle 2	
9-Sep	1	20.02	22.69	First Angle	0	45	135	0
				Tolerance	90	20	20	90
				Lag	25	40	20	0.3
				No. of Lags	9	10	9	16
				Range	200	284	160	1
				Nugget	0.66	0.6	0.6	0.65
				C1	0.51	0.6	0.6	0.48
				Sill	1.17	1.2	1.2	1.13
				Search Radius				2
				Block Size				0.05
9-Sep	2	27.42	28.69	First Angle	0			
				Tolerance	90			
				Lag	30			
				No. of Lags	10			
				Range	81			
				Nugget	0.52			
				C1	0.59			
				Sill	1.11			
				Search Radius	2			
				Block Size	10			
9-Sep	3	25.46	29.86	First Angle	0			
				Tolerance	90			
				Lag	20			
				No. of Lags	7			
				Range	23			
				Nugget	0.41			
				C1	0.66			
				Sill	1.07			
				Search Radius	46			
				Block Size	10			
10-Sep	1	20.03	25.18	First Angle	0			
				Tolerance	90			
				Lag	40			
				No. of Lags	10			
				Range	168			
				Nugget	0.67			
				C1	0.35			
				Sill	1.02			
				Search Radius	336			
				Block Size	30			

Table A1.1. (cont).

Date	Region	Start Time	End Time	Parameter	Omnidirectional Variograms	Anisotropic Variograms		Omnidirectional Rotated Variogram
					Value	Value		Value
						Angle 1	Angle 2	
11-Sep	1	20.11	24.35	First Angle	0			
				Tolerance	90			
				Lag	34			
				No. of Lags	10			
				Range	86			
				Nugget	0.72			
				C1	0.29			
				Sill	1.01			
				Search Radius	172			
				Block Size	15			
11-Sep	2	25.80	31.27	First Angle	0			
				Tolerance	90			
				Lag	23			
				No. of Lags	12			
				Range	172			
				Nugget	0.8			
				C1	0.28			
				Sill	1.08			
				Search Radius	344			
				Block Size	10			
16-Sep	1	23.56	32.39	First Angle	0			
				Tolerance	90			
				Lag	90			
				No. of Lags	6			
				Range	305			
				Nugget	0.94			
				C1	0.1			
				Sill	1.04			
				Search Radius	610			
				Block Size	15			
16-Sep	2	20.40	21.31	First Angle	0			
				Tolerance	90			
				Lag	130			
				No. of Lags	6			
				Range	377			
				Nugget	0.89			
				C1	0.17			
				Sill	1.06			
				Search Radius	754			
				Block Size	25			

Table A1.1. (cont).

Date	Region	Start Time	End Time	Parameter	Omnidirectional Variograms Value	Anisotropic Variograms Value Angle 1	Anisotropic Variograms Value Angle 2	Omnidirectional Rotated Variogram Value
17-Sep	1	21.15	24.82	First Angle	0			
				Tolerance	90			
				Lag	45			
				No. of Lags	10			
				Range	330			
				Nugget	0.9			
				C1	0.14			
				Sill	1.04			
				Search Radius	660			
				Block Size	15			
19-Sep	1	0.84	2.50	First Angle	0	0	90	0
				Tolerance	90	20	40	90
				Lag	100	100	18	0.52
				No. of Lags	7	8	7	8
				Range	470	500	70	1
				Nugget	0.95	0.7	0.7	0.88
				C1	0.1	0.7	0.7	0.14
				Sill	1.05	1.4	1.4	1.02
				Search Radius				2
				Block Size				0.1
19-Sep	1	5.02	6.34	First Angle	0			
				Tolerance	90			
				Lag	80			
				No. of Lags	7			
				Range	234			
				Nugget	0.86			
				C1	0.2			
				Sill	1.06			
				Search Radius	468			
				Block Size	10			
22-Sep	1	19.59	21.90	First Angle	0			
				Tolerance	90			
				Lag	20			
				No. of Lags	6			
				Range	34			
				Nugget	0.85			
				C1	0.19			
				Sill	1.06			
				Search Radius	68			
				Block Size	5			

Table A1.1. (cont).

					Omnidirectional Variograms	Anisotropic Variograms		Omnidirectional Rotated Variogram
Date	Region	Start Time	End Time	Parameter	Value	Value		Value
						Angle 1	Angle 2	
22-Sep	1	19.48	24.89	First Angle	0			
				Tolerance	90			
				Lag	7			
				No. of Lags	7			
				Range	22.5			
				Nugget	0.65			
				C1	0.4			
				Sill	1.05			
				Search Radius	45			
				Block Size	20			
23-Sep	1	15.83	16.91	First Angle	0			
				Tolerance	90			
				Lag	17			
				No. of Lags	6			
				Range	12			
				Nugget	1			
				C1	0.1			
				Sill	1.1			
				Search Radius	24			
				Block Size	5			
25-Sep	1	01.25	08.56	First Angle	0			
				Tolerance	90			
				Lag	70			
				No. of Lags	15			
				Range	800			
				Nugget	0.9			
				C1	0.25			
				Sill	1.15			
				Search Radius	1600			
				Block Size	20			
25-Sep	2	02.41	05.19	First Angle	0			
				Tolerance	90			
				Lag	70			
				No. of Lags	7			
				Range	200			
				Nugget	0.54			
				C1	0.7			
				Sill	1.24			
				Search Radius	400			
				Block Size	10			

Table A1.1. (cont).

Date	Region	Start Time	End Time	Parameter	Omnidirectional Variograms	Anisotropic Variograms		Omnidirectional Rotated Variogram
					Value	Value		Value
						Angle 1	Angle 2	
26-Sep	1	15.96	17.92	First Angle	0			
				Tolerance	90			
				Lag	65			
				No. of Lags	10			
				Range	280			
				Nugget	0.89			
				C1	0.24			
				Sill	1.13			
				Search Radius	560			
				Block Size	15			
26-Sep	1	18.50	19.95	First Angle	0			
				Tolerance	90			
				Lag	120			
				No. of Lags	7			
				Range	460			
				Nugget	0.89			
				C1	0.21			
				Sill	1.1			
				Search Radius	920			
				Block Size	15			
28-Sep	1	18.63	20.42	First Angle	0			
				Tolerance	90			
				Lag	25			
				No. of Lags	12			
				Range	72			
				Nugget	0.68			
				C1	0.39			
				Sill	1.07			
				Search Radius	144			
				Block Size	7			
28-Sep	2	25.38	25.58	First Angle	0			
				Tolerance	90			
				Lag	17			
				No. of Lags	11			
				Range	140			
				Nugget	0.1			
				C1	1			
				Sill	1.1			
				Search Radius	280			
				Block Size	10			

Table A1.1. (cont).

					Omnidirectional Variograms	Anisotropic Variograms		Omnidirectional Rotated Variogram
					Value	Value		Value
Date	Region	Start Time	End Time	Parameter		Angle 1	Angle 2	
29-Sep	1	18.66	19.19	First Angle	0			
				Tolerance	90			
				Lag	50			
				No. of Lags	7			
				Range	55			
				Nugget	0.46			
				C1	0.65			
				Sill	1.11			
				Search Radius	110			
				Block Size	5			
29-Sep	2	19.32	21.78	First Angle	0	65	155	0
				Tolerance	90	10	30	90
				Lag	40	50	55	0.85
				No. of Lags	5	6	5	8
				Range	112	113	37	1
				Nugget	0.9	0.7	0.4	0.86
				C1	0.13	0.4	0.7	0.16
				Sill	1.03	1.1	1.1	1.02
				Search Radius				2
				Block Size				0.15
30-Sep	1	19.39	21.27	First Angle	0	30	120	0
				Tolerance	90	30	30	90
				Lag	60	60	30	0.41
				No. of Lags	12	6	6	8
				Range	385	250	160	1
				Nugget	0.72	0.4	0.4	0.7
				C1	0.39	0.7	0.7	0.32
				Sill	1.11	1.1	1.1	1.02
				Search Radius				2
				Block Size				0.1

Table A1.1. (cont).

Date	Region	Start Time	End Time	Parameter	Omnidirectional Variograms	Anisotropic Variograms		Omnidirectional Rotated Variogram
					Value	Value		Value
						Angle 1	Angle 2	
Purse Seine								
23-Aug	1	25.01	28.35	First Angle	0			
				Tolerance	90			
				Lag	200			
				No. of Lags	5			
				Range	410			
				Nugget	0.53			
				C1	0.49			
				Sill	1.02			
				Search Radius	820			
				Block Size	100			
28-Aug	1	23.63	24.60	First Angle	0	70	160	0
				Tolerance	90	30	40	90
				Lag	200	250	250	0.27
				No. of Lags	10	16	11	9
				Range	1700	1240	2800	1
				Nugget	0.14	0	0	0.06
				C1	1.1	1.6	1.6	1.14
				Sill	1.24	1.6	1.6	1.2
				Search Radius				2
				Block Size				0.03
14-Sep	1	25.61	28.85	First Angle	0	30	120	0
				Tolerance	90	20	20	90
				Lag	240	240	120	0.21
				No. of Lags	9	9	6	10
				Range	1178	1200	395	1
				Nugget	0.69	0.55	0.55	0.64
				C1	0.42	0.57	0.57	0.42
				Sill	1.11	1.12	1.12	1.06
				Search Radius				2
				Block Size				0.1
14-Sep	2	22.48	25.24	First Angle	0			
				Tolerance	90			
				Lag	210			
				No. of Lags	7			
				Range	1440			
				Nugget	0.23			
				C1	1.2			
				Sill	1.43			
				Search Radius	2880			
				Block Size	40			

Table A1.1. (cont).

Date	Region	Start Time	End Time	Parameter	Omnidirectional Variograms	Anisotropic Variograms		Omnidirectional Rotated Variogram
					Value	Value		Value
						Angle 1	Angle 2	
15-Sep	1	20.98	21.44	First Angle	0			
				Tolerance	90			
				Lag	70			
				No. of Lags	5			
				Range	240			
				Nugget	0.06			
				C1	1.2			
				Sill	1.26			
				Search Radius	480			
				Block Size	10			
15-Sep	2	25.35	29.66	First Angle	0			
				Tolerance	90			
				Lag	240			
				No. of Lags	11			
				Range	912			
				Nugget	0.45			
				C1	0.67			
				Sill	1.12			
				Search Radius	1824			
				Block Size	100			
26-Sep	1	20.39	22.86	First Angle	0			
				Tolerance	90			
				Lag	225			
				No. of Lags	6			
				Range	1000			
				Nugget	0.4			
				C1	0.97			
				Sill	1.37			
				Search Radius	2000			
				Block Size	30			
26-Sep	1	27.59	27.92	First Angle	0			
				Tolerance	90			
				Lag	200			
				No. of Lags	5			
				Range	570			
				Nugget	0			
				C1	1.3			
				Sill	1.3			
				Search Radius	1140			
				Block Size	30			

Table A1.1. (cont).

Date	Region	Start Time	End Time	Parameter	Omnidirectional Variograms	Anisotropic Variograms		Omnidirectional Rotated Variogram
					Value	Value		Value
						Angle 1	Angle 2	
26-Sep	2	27.00	27.30	First Angle	0			
				Tolerance	90			
				Lag	90			
				No. of Lags	7			
				Range	438			
				Nugget	0.48			
				C1	0.74			
				Sill	1.22			
				Search Radius	876			
				Block Size	15			
26-Sep	3	23.29	26.91	First Angle	0	0	90	0
				Tolerance	90	30	30	90
				Lag	310	90	305	0.34
				No. of Lags	7	10	6	10
				Range	854	373	900	1
				Nugget	0.66	0.5	0.5	0.64
				C1	0.44	0.72	0.72	0.44
				Sill	1.1			1.08
				Search Radius				2
				Block Size				0.1
27-Sep	1	24.27	29.15	First Angle	0	0	90	0
				Tolerance	90	30	30	90
				Lag	200	200	200	0.39
				No. of Lags	6	6	8	6
				Range	400	268	800	1
				Nugget	0.52	0.52	0.52	0.53
				C1	0.545	0.77	0.77	0.55
				Sill	1.065			1.08
				Search Radius				2
				Block Size				0.1
27-Sep	2	29.33	29.49	First Angle	0			
				Tolerance	90			
				Lag	60			
				No. of Lags	8			
				Range	400			
				Nugget	0			
				C1	1.5			
				Sill	1.5			
				Search Radius	800			
				Block Size	15			

Appendix 1. Figures A1.1 – A 1.38. Components of block kriging analysis for indicated fishing nights. Data pertains to an individual region fished on the given night and as a result, times are not continuous. Each figure is formatted as follows. (A) Contour plot of data to identify high and low density areas. (B) Histogram of density distributions to determine if there are any distributional effects to consider in the analysis. (C) Variogram cloud to identify any patterns that should be considered for initial lags. (D) Initial omnidirectional variogram to provide basis for investigating anisotropy. (E) Omnidirectional varigram surface to identify possible anisotropic effects. (F) Anisotropic variograms as a prelude to anisotropic modeling if required. (G) Anisotropic variogram model shown if required. This modeling was often not required and in those cases this panel is left blank. (H) Relative densities for block kriging estimate using the most appropriate variogram model.

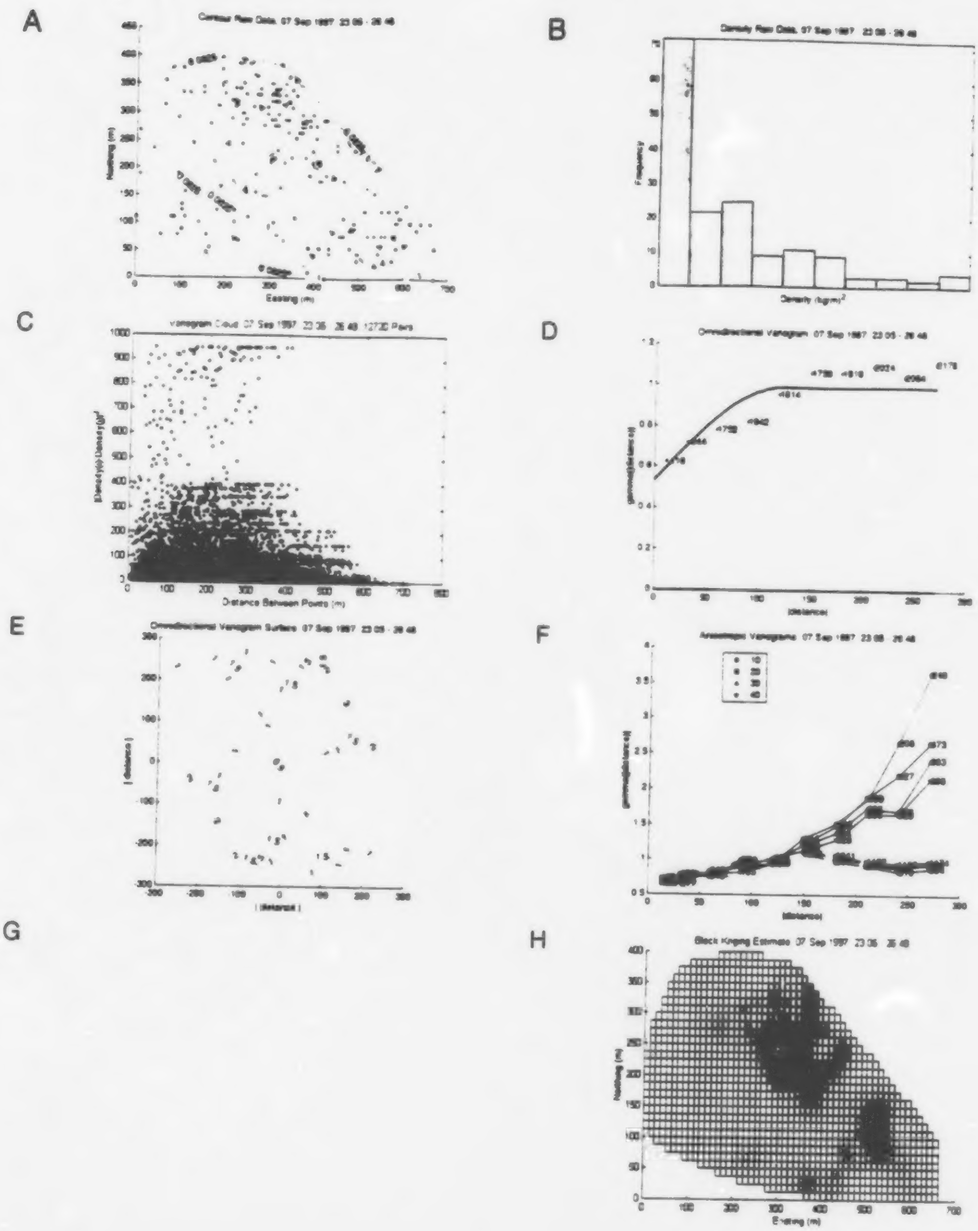


Fig. A1.1. Components for block kriging analysis for gillnetter data 7 Sep 1997, region 01, between 23.05 and 26.48. Variogram surface and variograms indicated that omnidirectional variogram was suitable for this analysis.

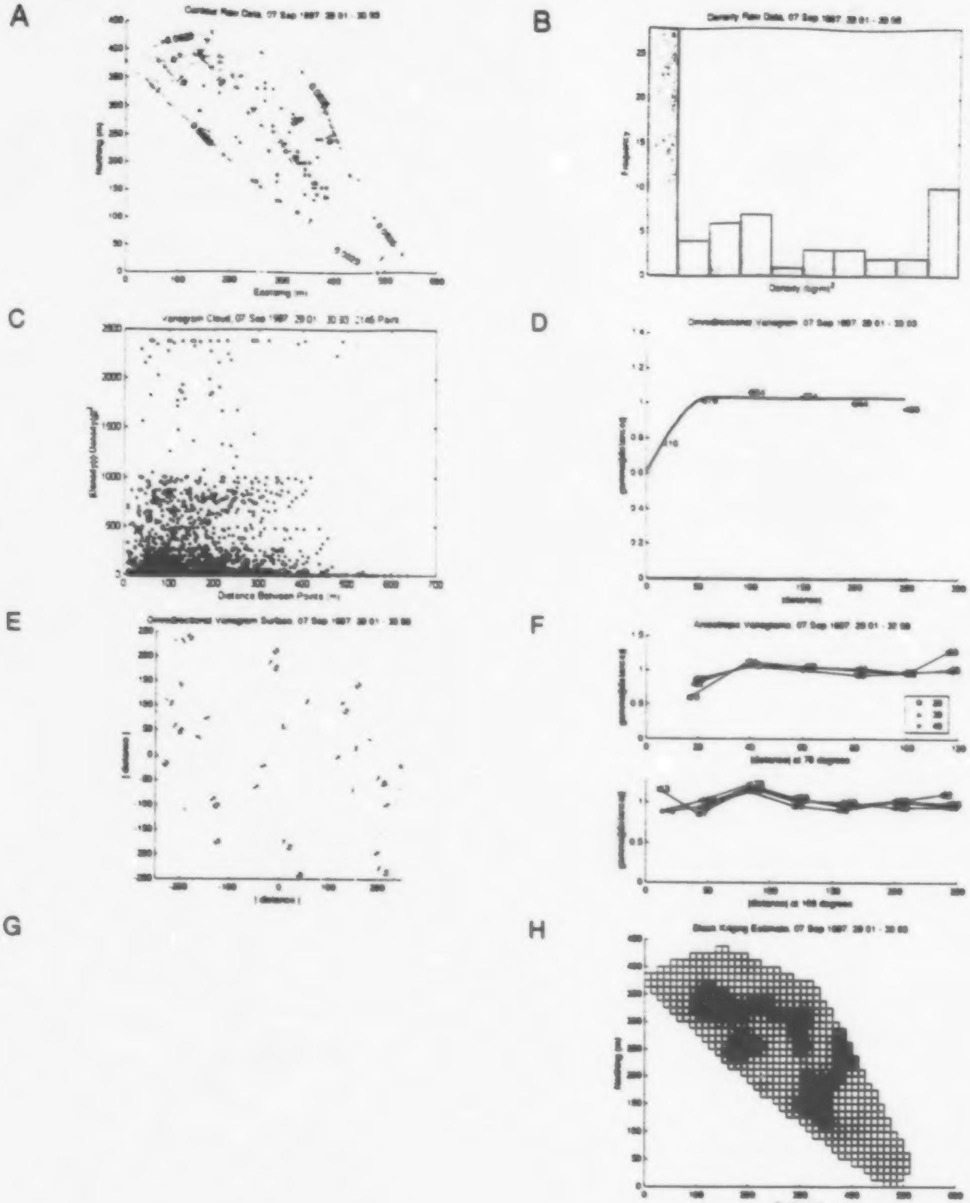


Fig. A1.2. Components for block kriging analysis for gillnetter data 7 Sep 1997, region 01, between 29.01 - 30.93. Variogram surface and variograms indicated that omnidirectional variogram was suitable for this analysis.

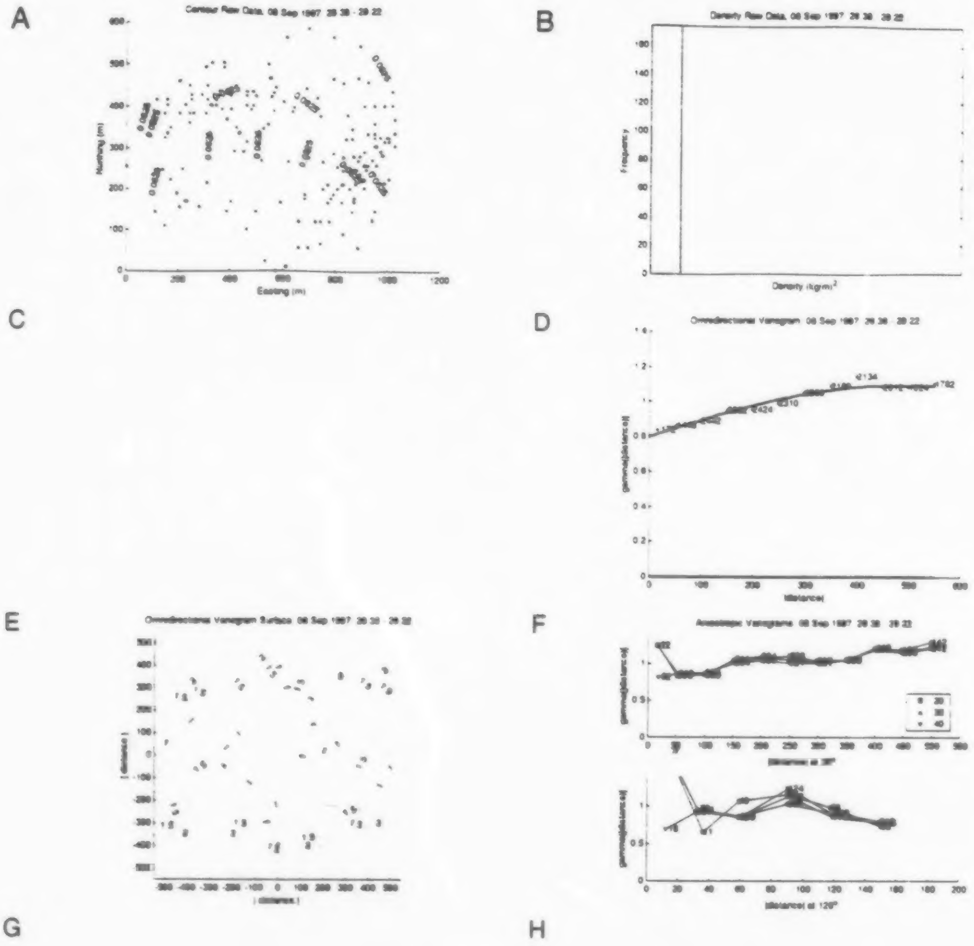


Fig. A1.3. Components for block kriging analysis for gillnetter data 8 Sep 1997, region 01, between 26.38 – 29.22. Variogram surface and variograms indicated that omnidirectional variogram was suitable for this analysis.

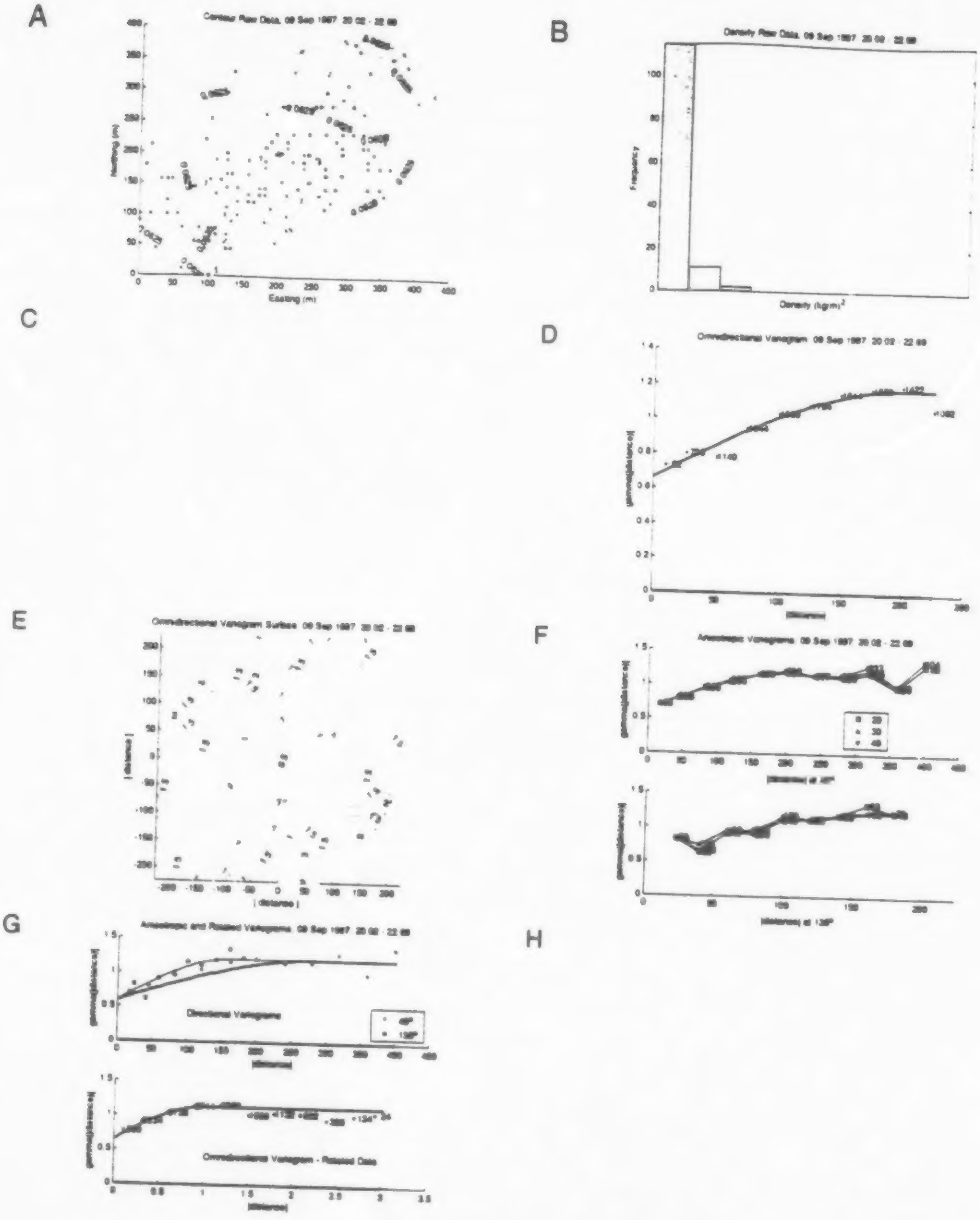


Fig. A1.4. Components for block kriging analysis for gillnetter data 9 Sep 1997, region 01, between 20.02 - 22.69. Variogram surface and variograms indicated that anisotropic variogram was suitable for this analysis.

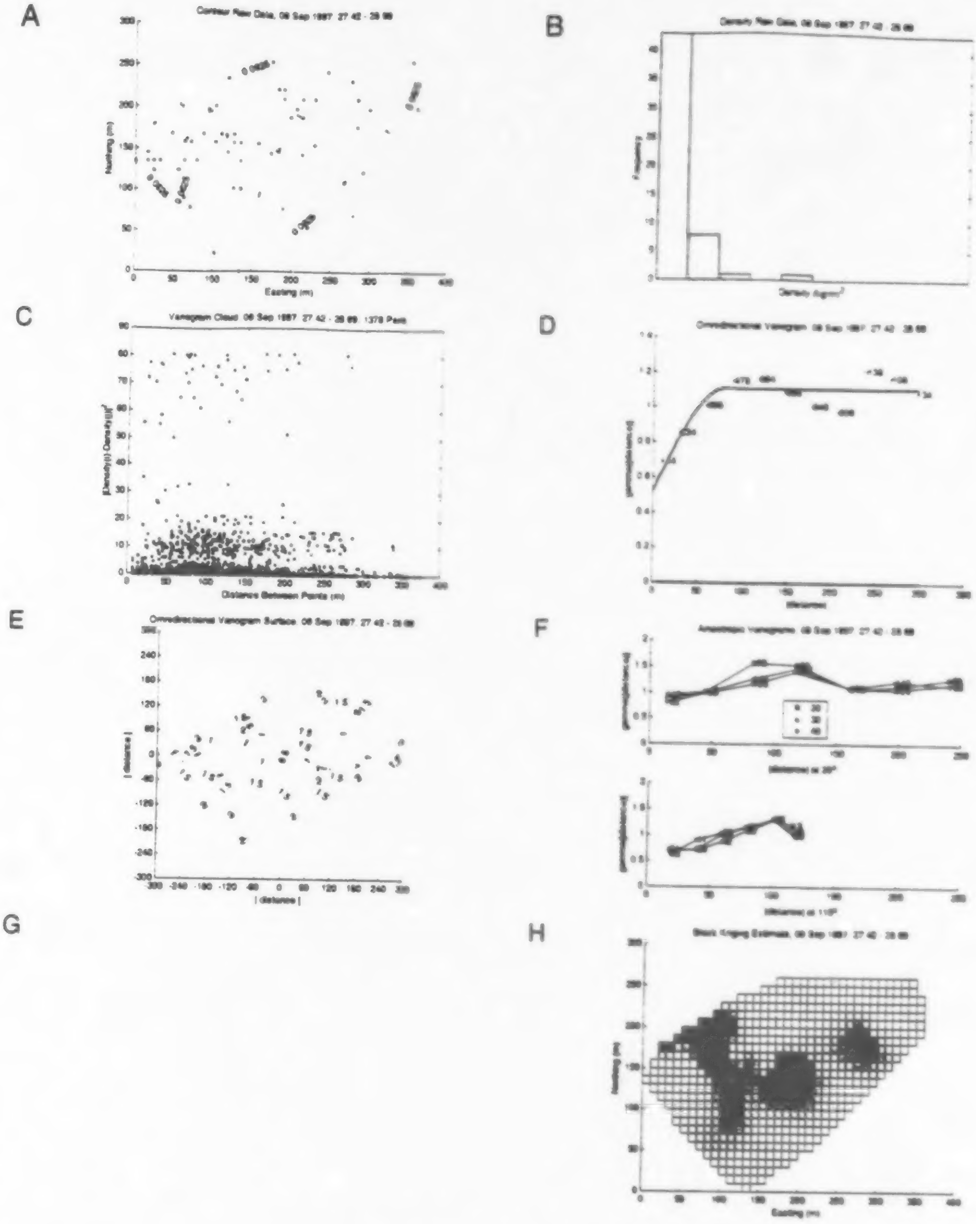


Fig. A1.5. Components for block kriging analysis for gillnetter data 9 Sep 1997, region 02, between 27.42 - 28.69. Variogram surface and variograms indicated that omnidirectional variogram was suitable for this analysis.

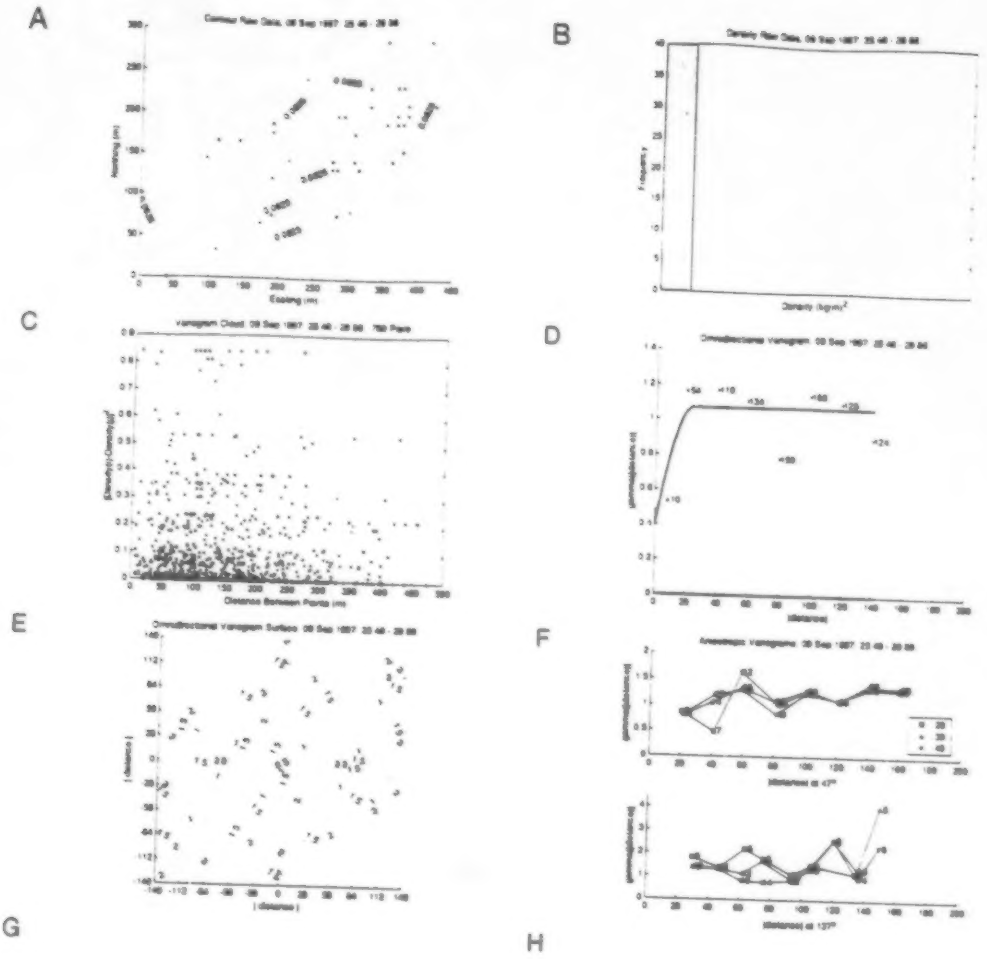


Fig. A1.6. Components for block kriging analysis for gillnetter data 9 Sep 1997, region 03, between 25.46 - 29.86. Variogram surface and variograms indicated that omnidirectional variogram was suitable for this analysis.

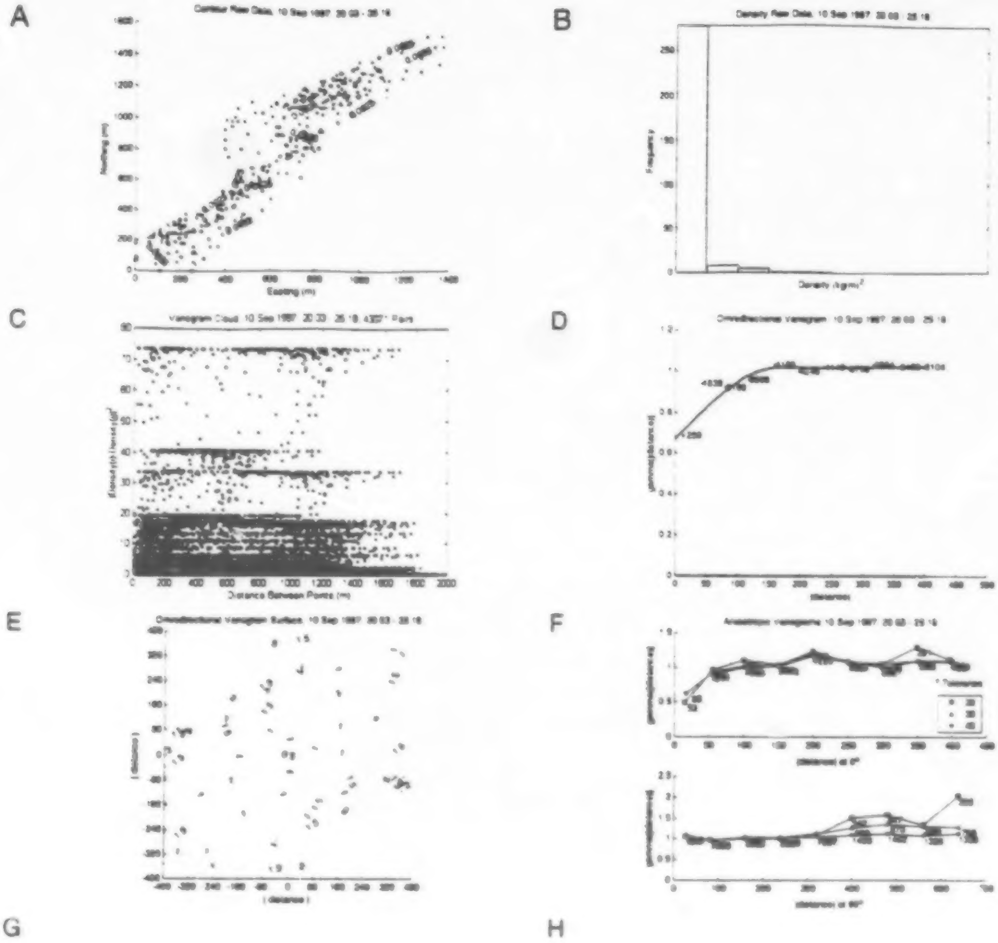


Fig. A1.7. Components for block kriging analysis for gillnetter data 10 Sep 1997, region 01, between 20.03 - 25.18. Variogram surface and variograms indicated that omnidirectional variogram was suitable for this analysis.

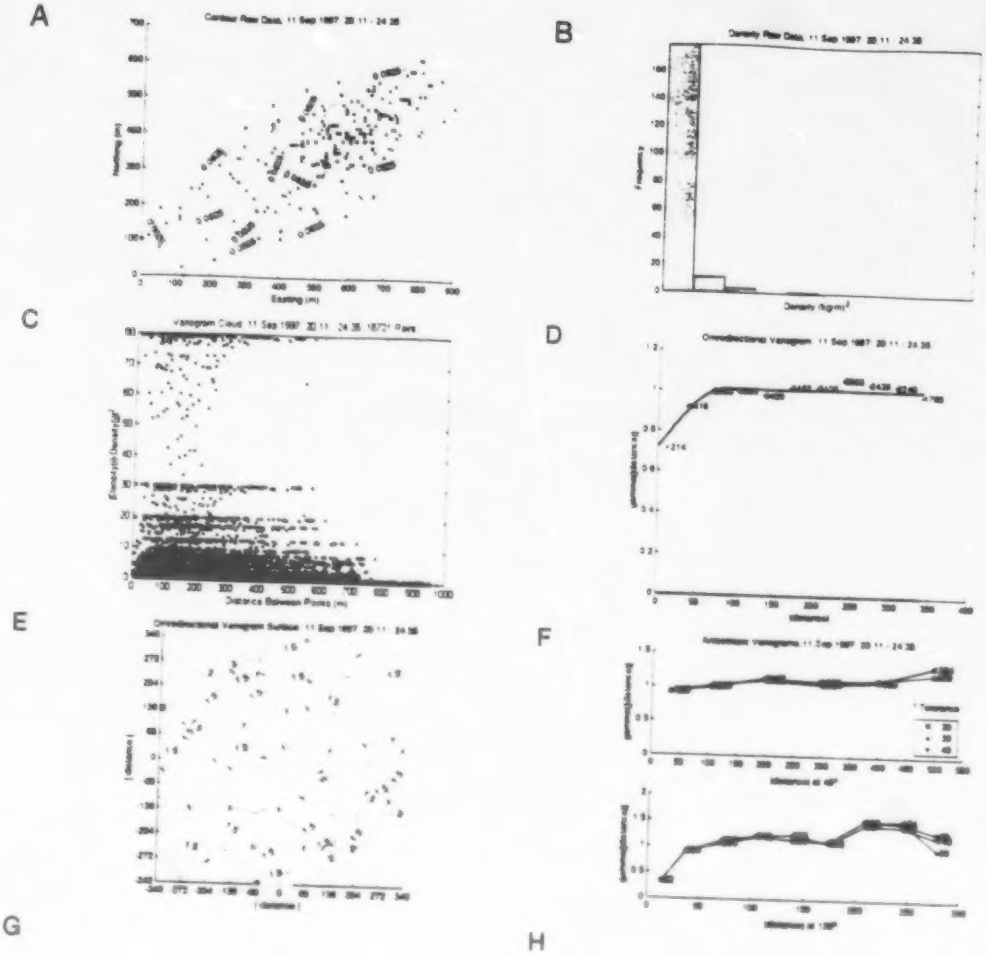


Fig. A1.8. Components for block kriging analysis for gillnetter data 11 Sep 1997, region 01, between 20.11 - 24.35. Variogram surface and variograms indicated that omnidirectional variogram was suitable for this analysis.

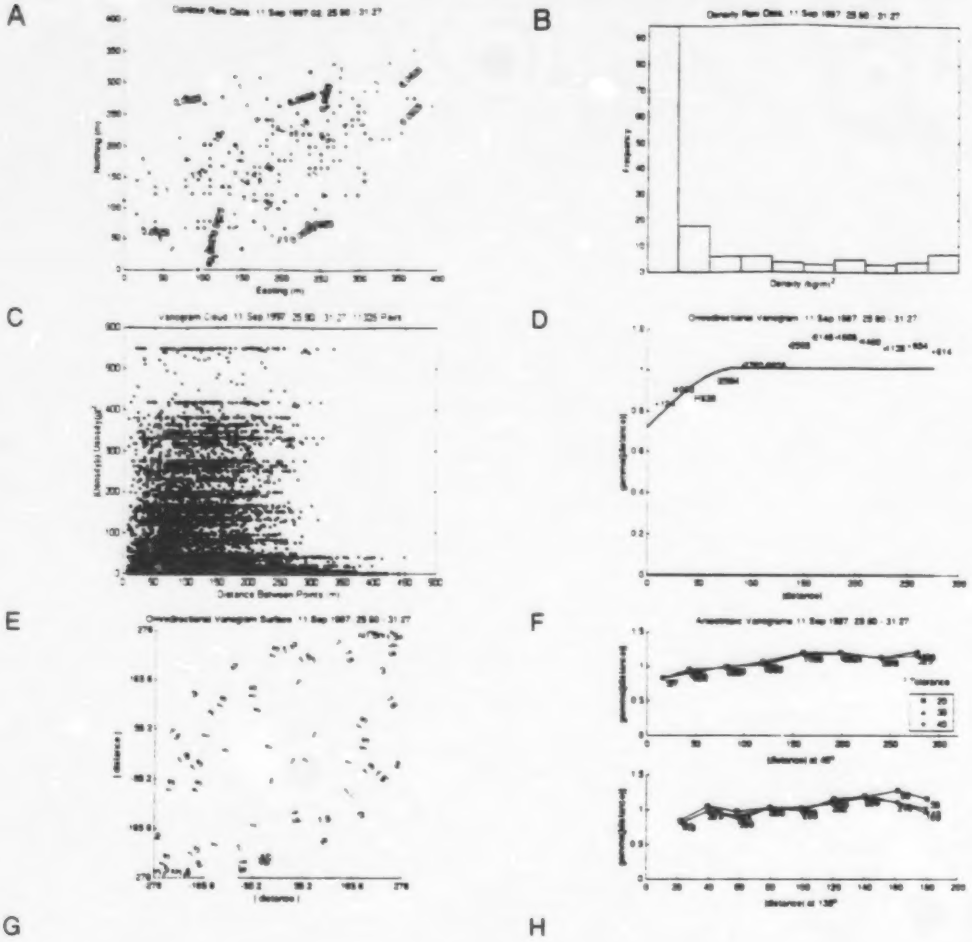


Fig. A1.9. Components for block kriging analysis for gillnetter data 11 Sep 1997, region 02, between 25.80 - 31.27. Variogram surface and variograms indicated that omnidirectional variogram was suitable for this analysis.

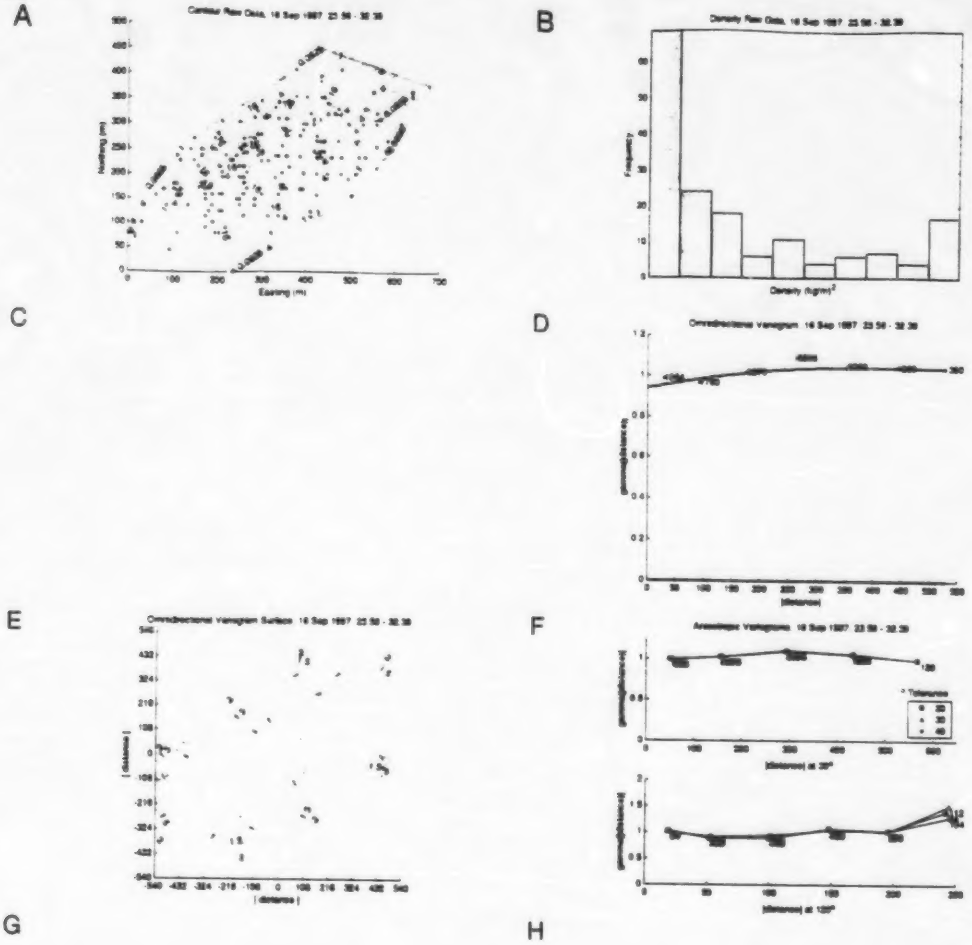
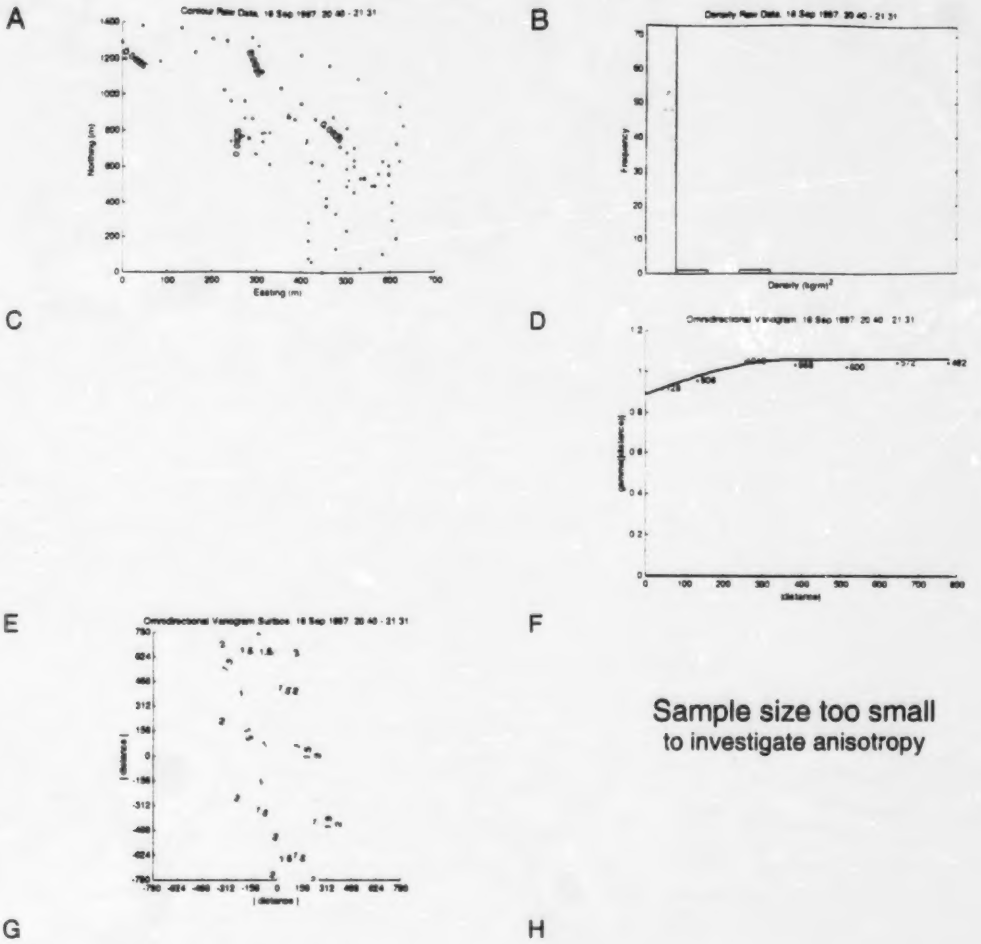


Fig. A1.10. Components for block kriging analysis for gillnetter data 16 Sep 1997, region 01, between 23.56 – 32.39. Variogram surface and variograms indicated that omnidirectional variogram was suitable for this analysis.



Sample size too small
to investigate anisotropy

Fig. A1.11. Components for block kriging analysis for gillnetter data 16 Sep 1997, region 02, between 20.40 – 21.31. Variogram surface and variograms indicated that omnidirectional variogram was suitable for this analysis.

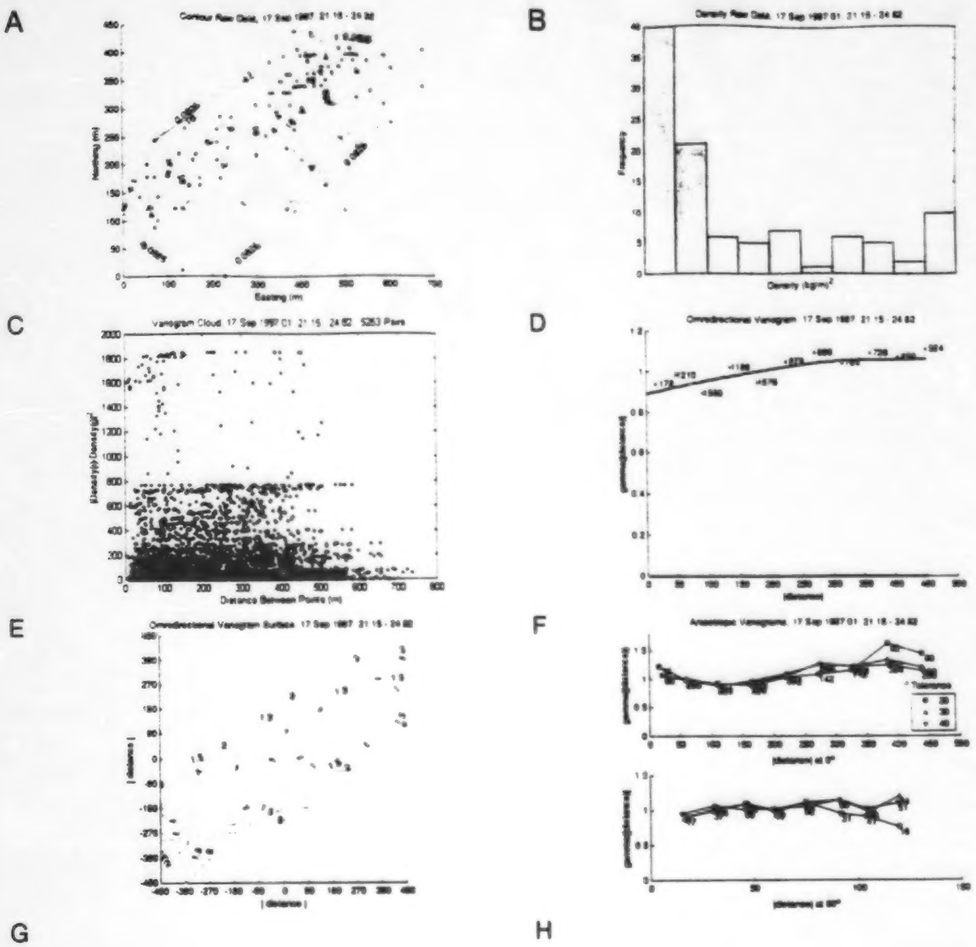


Fig. A1.12. Components for block kriging analysis for gillnetter data 17 Sep 1997, region 01, between 21.15 - 24.82. Variogram surface and variograms indicated that omnidirectional variogram was suitable for this analysis.

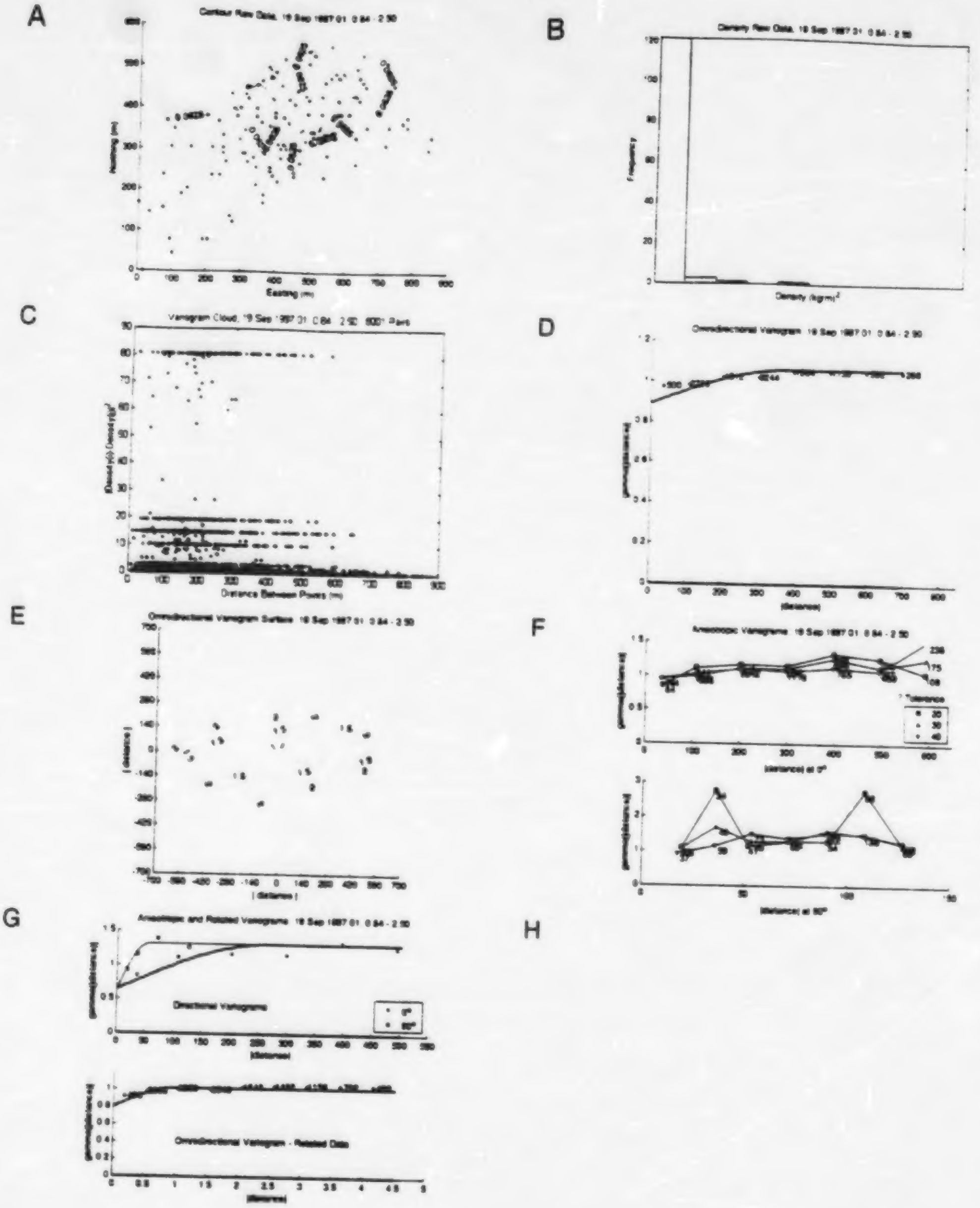


Fig. A1.13. Components for block kriging analysis for gillnetter data 19 Sep 1997, region 01, between 0.84 - 2.50. Variogram surface and variograms indicated that anisotropic variogram was suitable for this analysis.

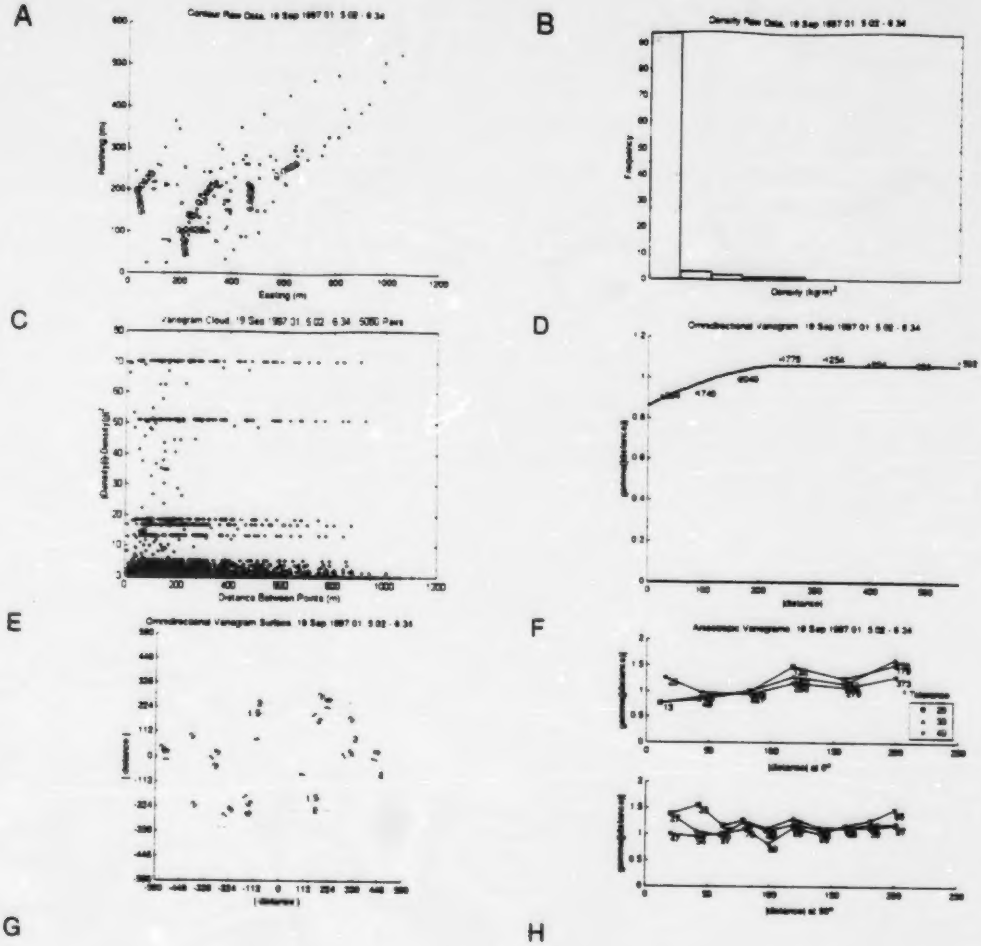
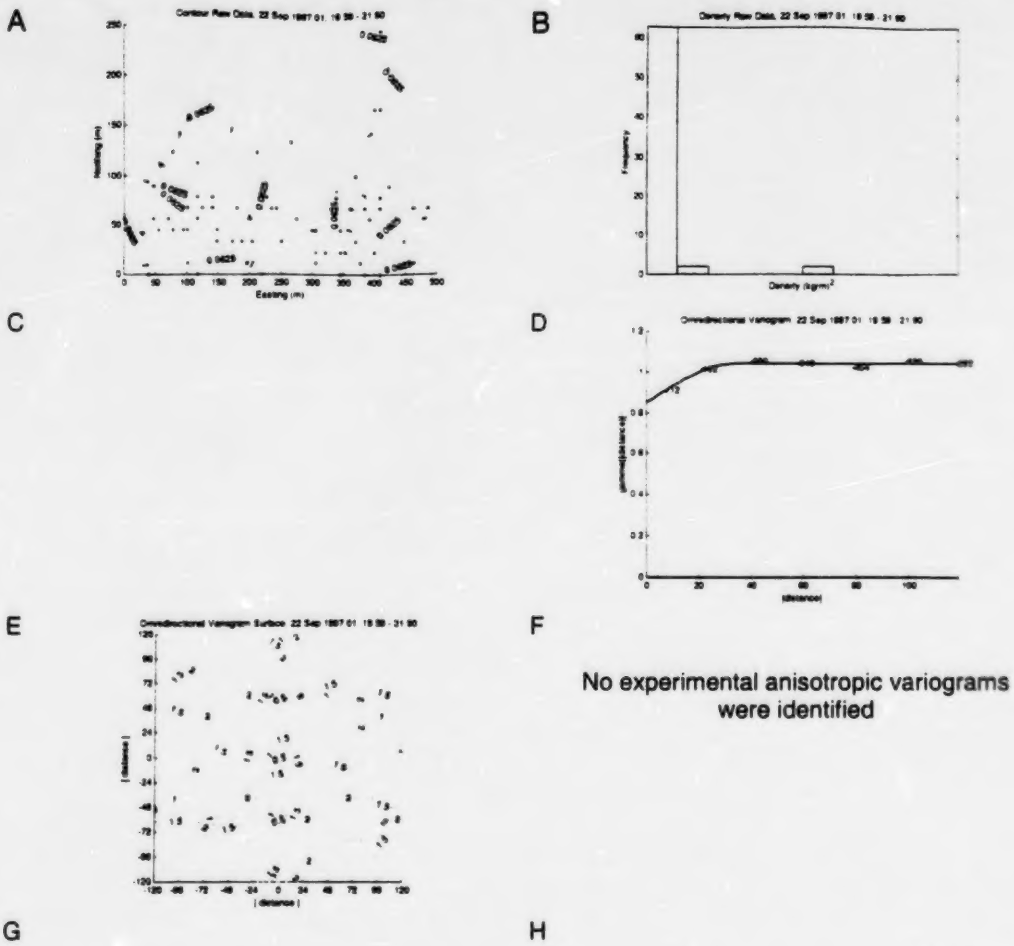
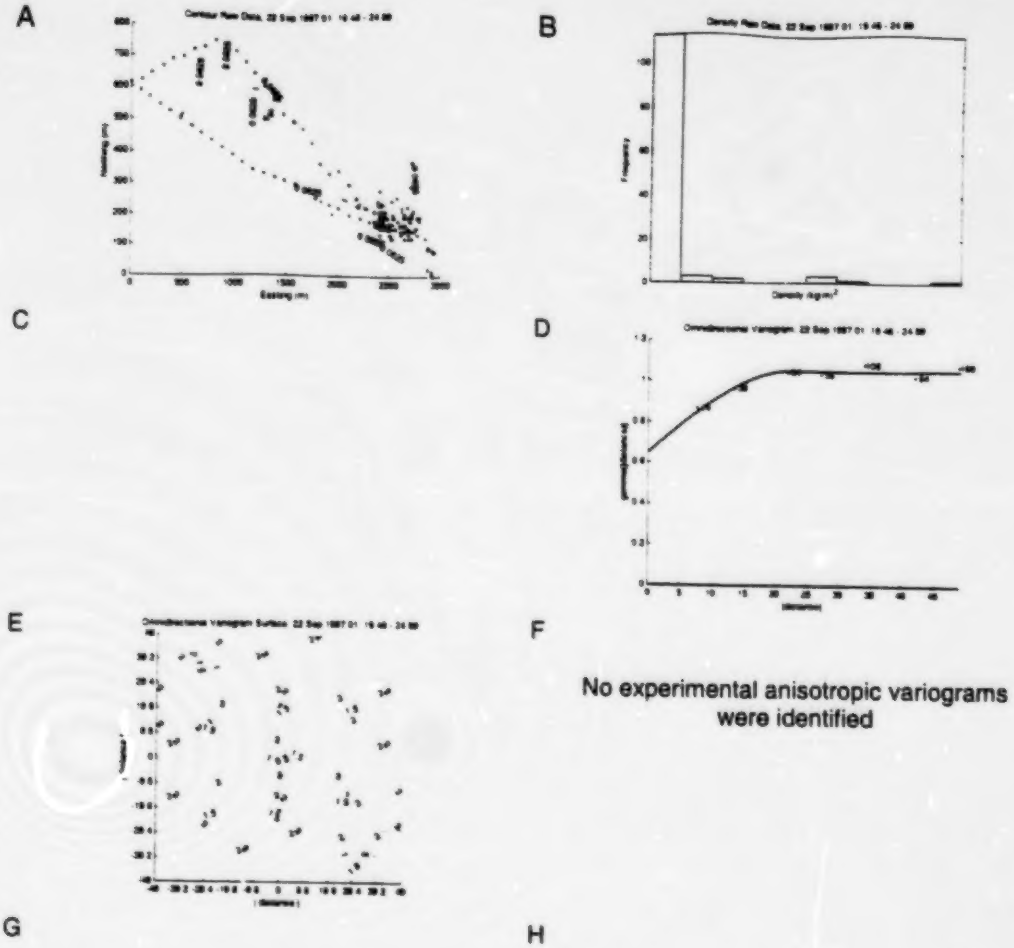


Fig. A1.14. Components for block kriging analysis for gillnetter data 19 Sep 1997, region 01, between 05.02 - 06.34. Variogram surface and variograms indicated that omnidirectional variogram was suitable for this analysis.



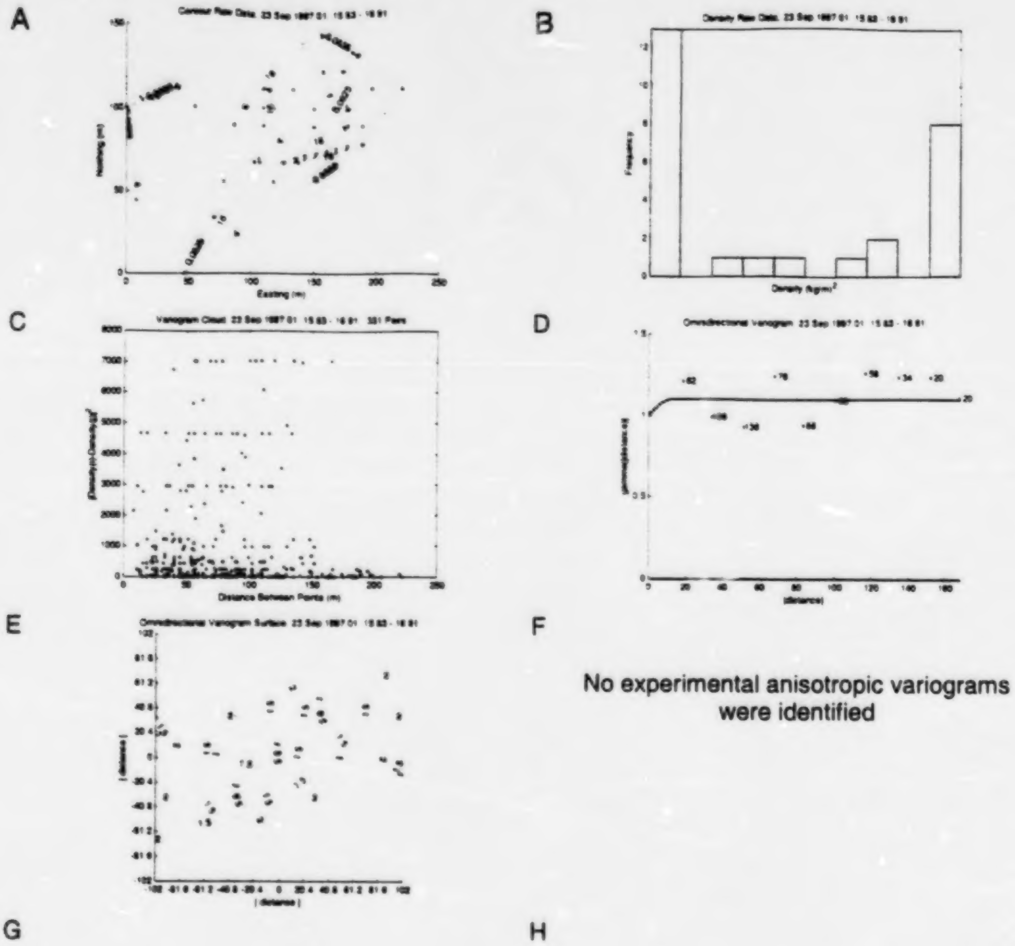
No experimental anisotropic variograms were identified

Fig. A1.15. Components for block kriging analysis for gillnetter data 22 Sep 1997, region 01, between 19.59 – 21.90. Variogram surface and variograms indicated that omnidirectional variogram was suitable for this analysis.



No experimental anisotropic variograms were identified

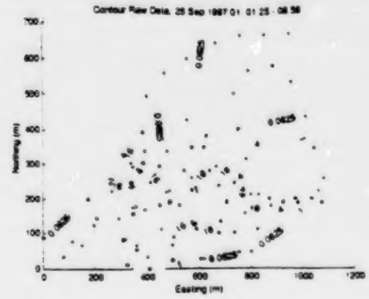
Fig. A1.16. Components for block kriging analysis for gillnetter data 22 Sep 1997, region 01, between 19.48 – 24.89. Variogram surface and variograms indicated that omnidirectional variogram was suitable for this analysis.



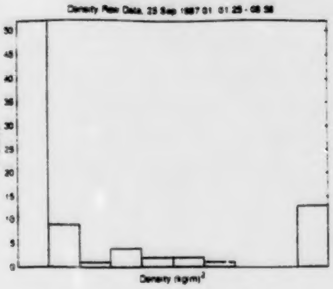
No experimental anisotropic variograms were identified

Fig. A1.17. Components for block kriging analysis for gillnetter data 23 Sep 1997, region 01, between 15.83 – 16.91. Variogram surface and variograms indicated that omnidirectional variogram was suitable for this analysis.

A

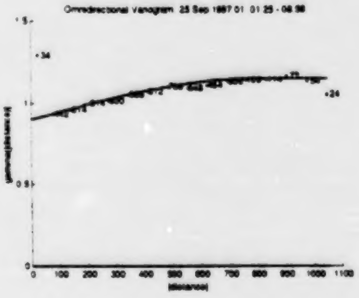


B

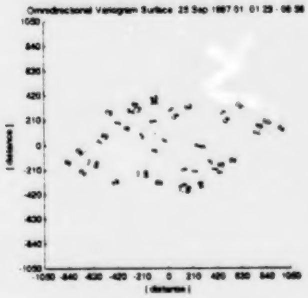


C

D



E



F

No experimental anisotropic variograms
were identified

G

H

Fig. A1.18. Components for block kriging analysis for gillnetter data 25 Sep 1997, region 01, between 01.25 – 08.56. Variogram surface and variograms indicated that omnidirectional variogram was suitable for this analysis.

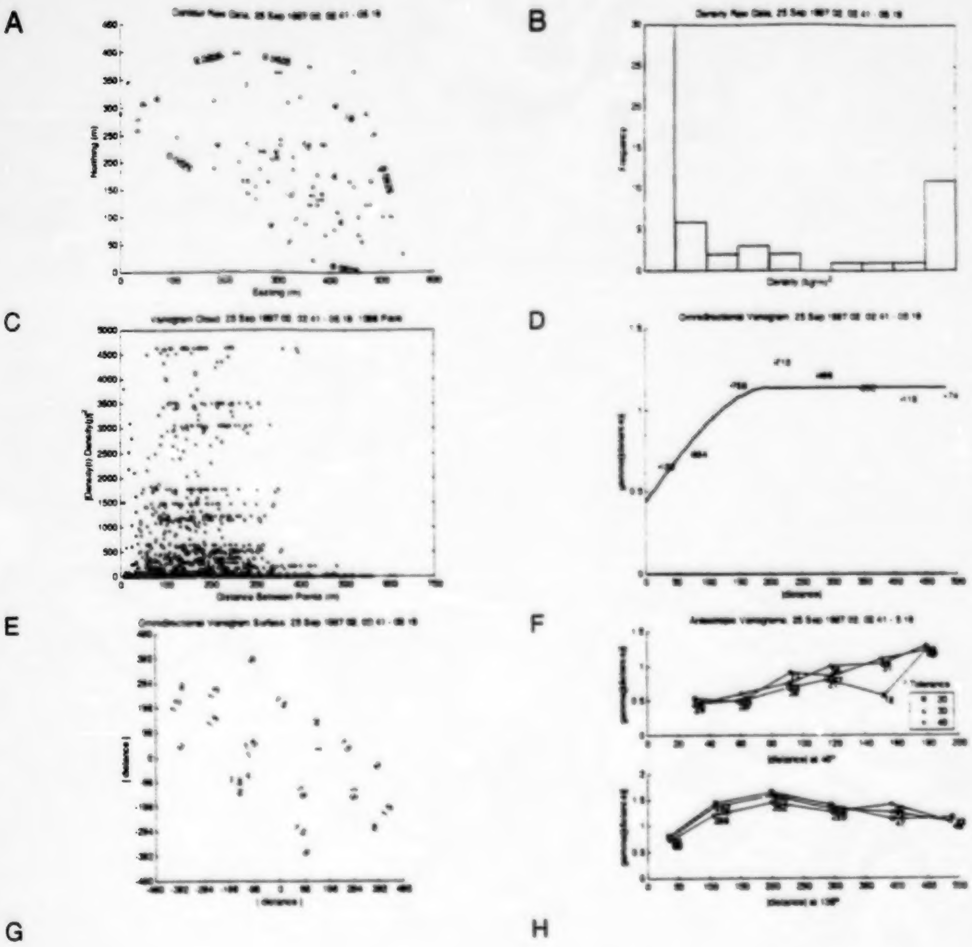
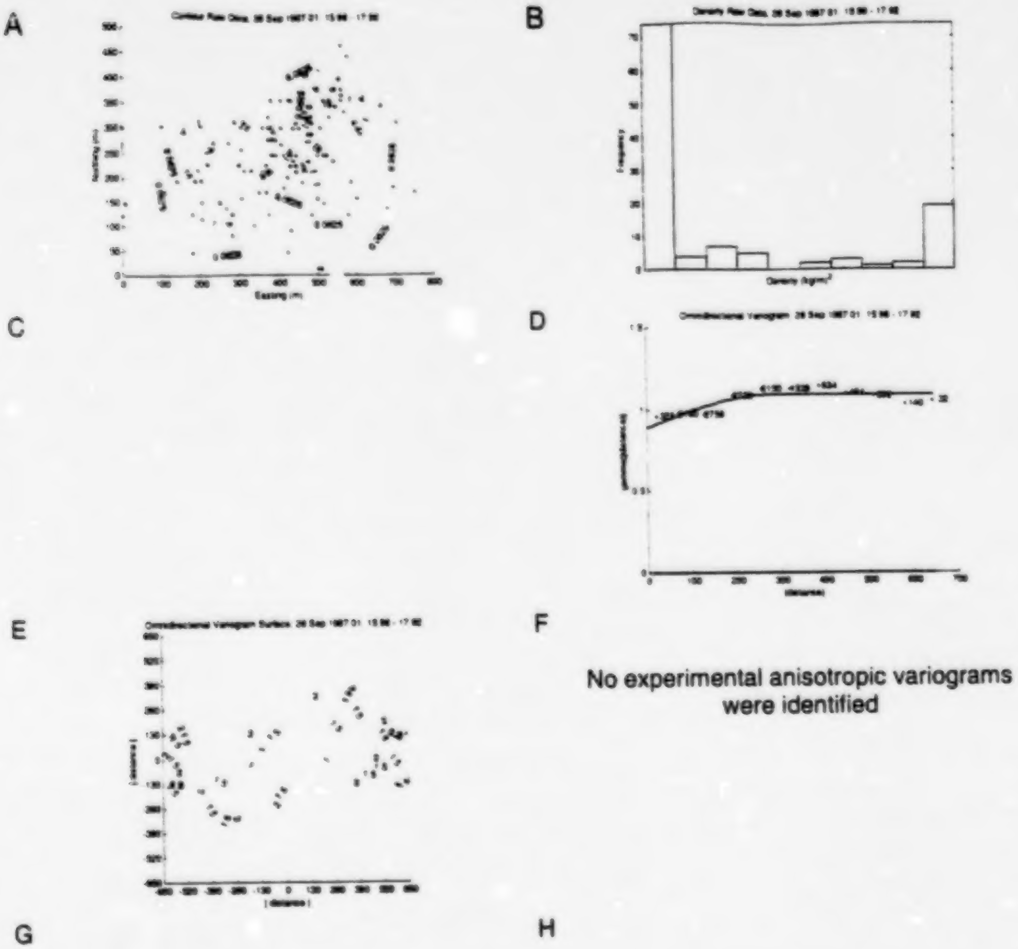


Fig. A1.19. Components for block kriging analysis for gillnetter data 25 Sep 1997, region 02, between 02.41 – 05.19. Variogram surface and variograms indicated that omnidirectional variogram was suitable for this analysis.



No experimental anisotropic variograms were identified

Fig. A1.20. Components for block kriging analysis for gillnetter data 26 Sep 1997, region 01, between 15.96 – 17.92. Variogram surface and variograms indicated that omnidirectional variogram was suitable for this analysis.

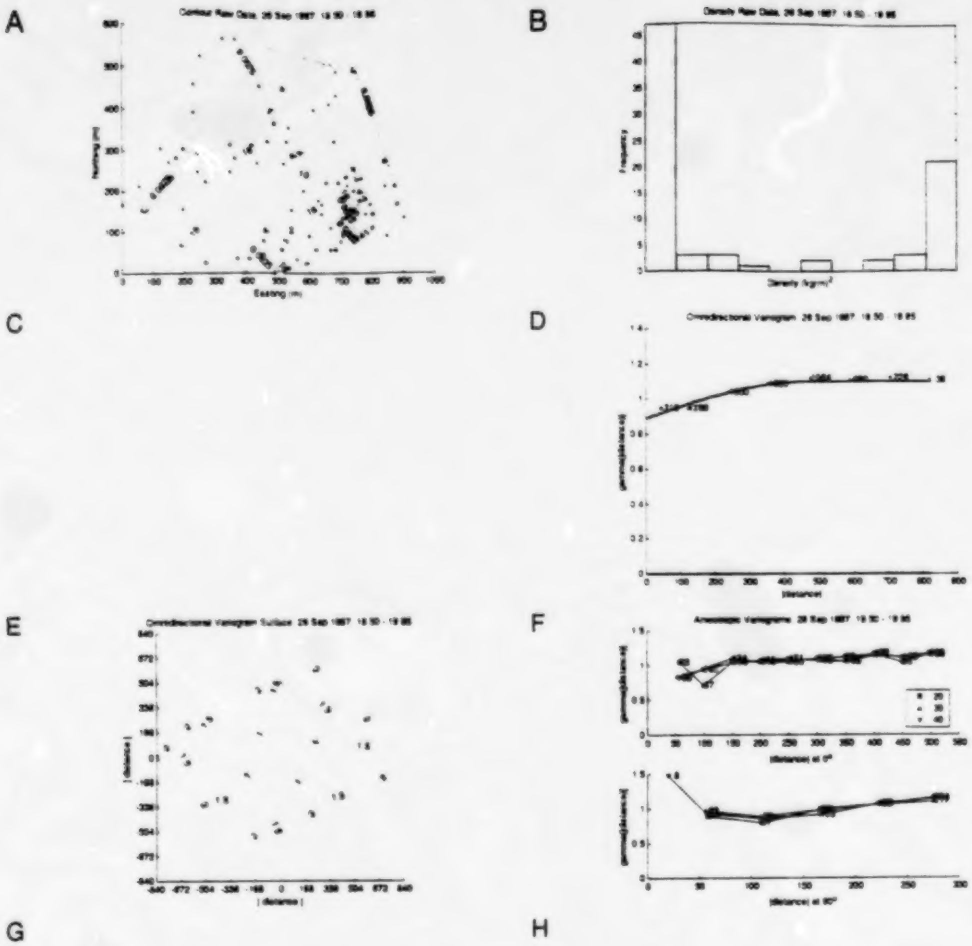
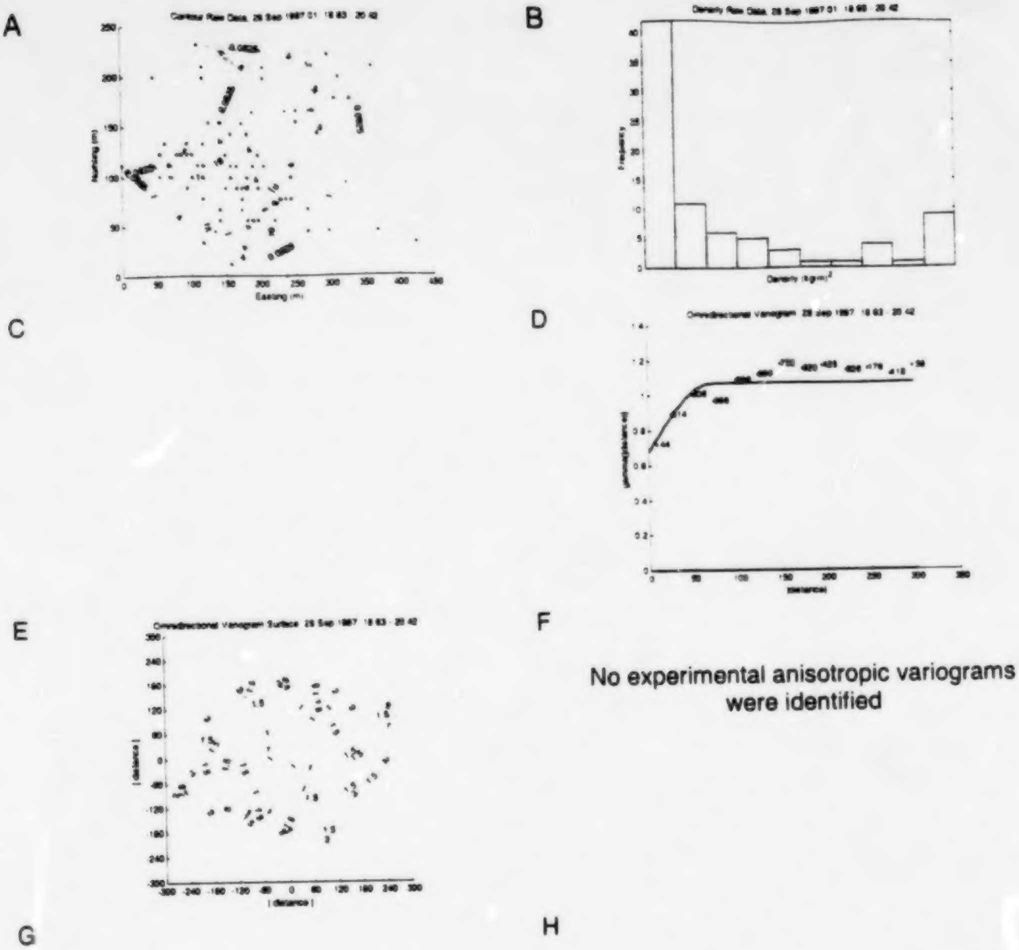


Fig. A1.21. Components for block kriging analysis for gillnetter data 26 Sep 1997, region 01, between 18.50 – 19.95. Variogram surface and variograms indicated that omnidirectional variogram was suitable for this analysis.



No experimental anisotropic variograms
were identified

Fig. A1.22. Components for block kriging analysis for gillnetter data 28 Sep 1997, region 01, between 18.63 - 20.42. Variogram surface and variograms indicated that omnidirectional variogram was suitable for this analysis.

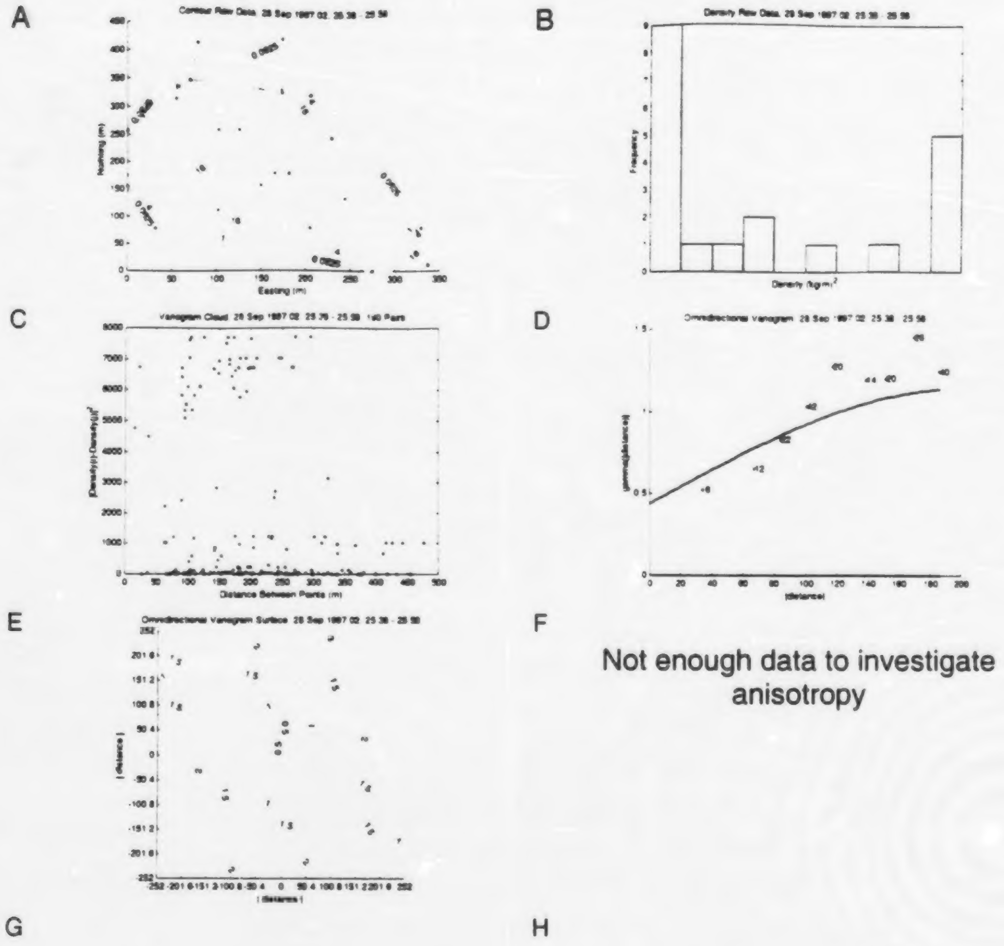
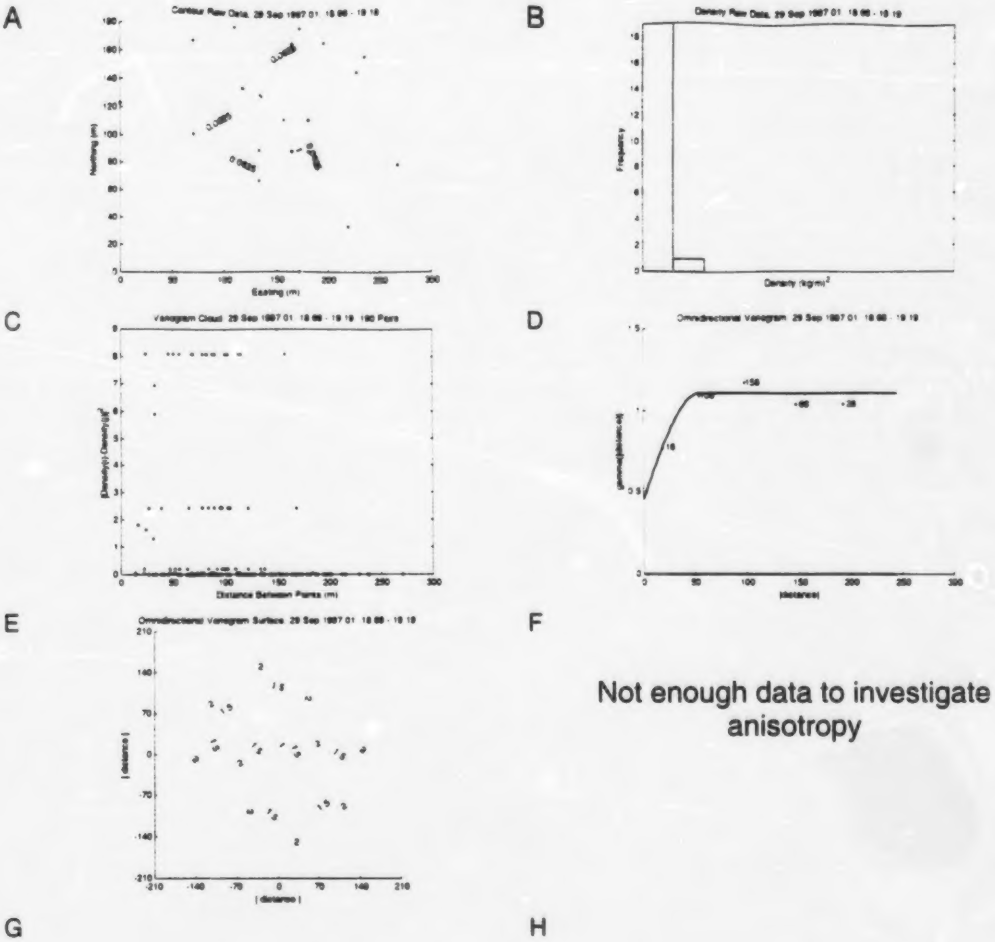


Fig. A1.23. Components for block kriging analysis for gillnetter data 28 Sep 1997, region 02, between 25.38 – 25.58. Variogram surface and variograms indicated that omnidirectional variogram was suitable for this analysis.



Not enough data to investigate anisotropy

Fig. A1.24. Components for block kriging analysis for gillnetter data 29 Sep 1997, region 01, between 18.66 – 19.19. Variogram surface and variograms indicated that omnidirectional variogram was suitable for this analysis

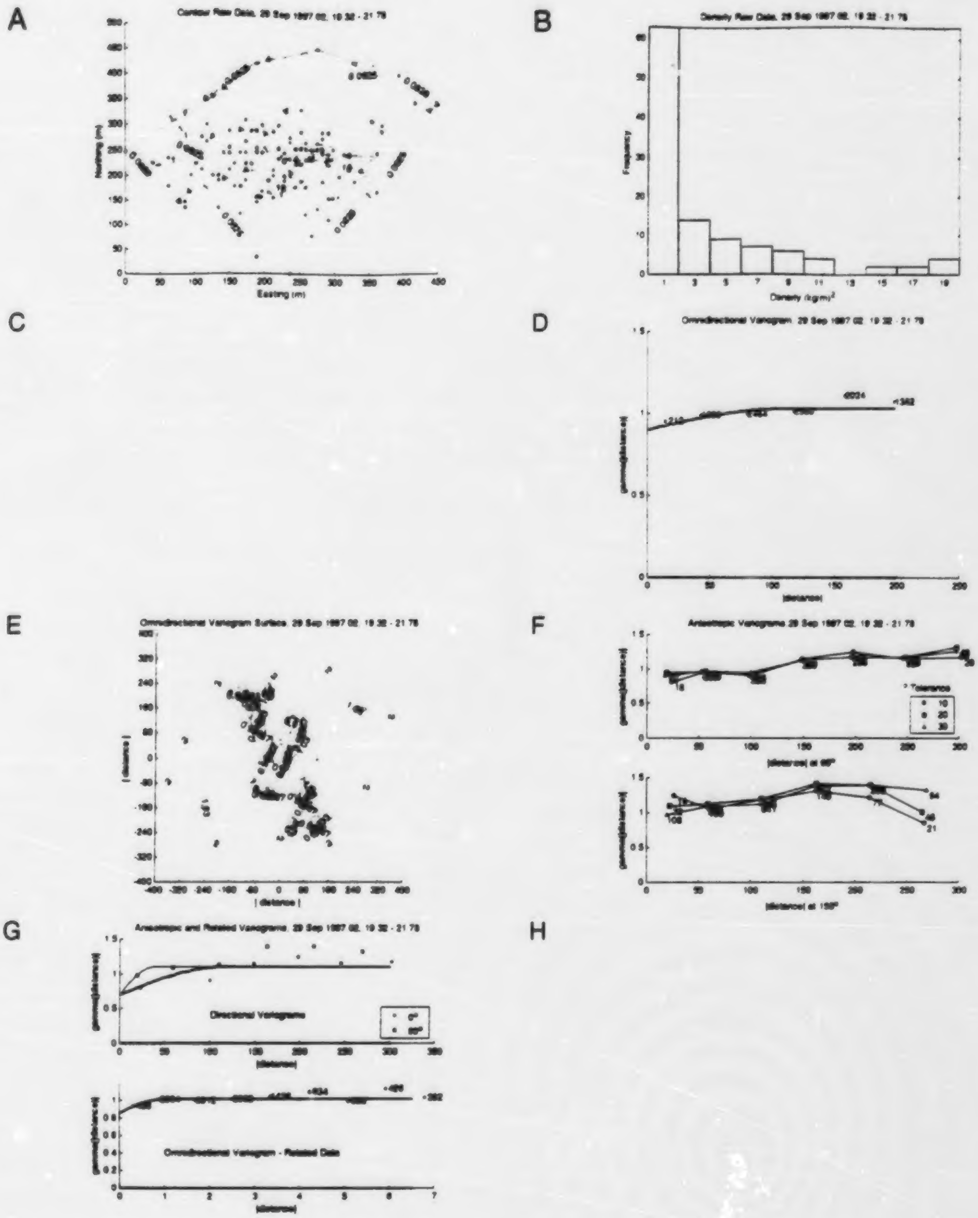


Fig. A1.25. Components for block kriging analysis for gillnetter data 29 Sep 1997, region 02, between 19.32 – 21.78. Variogram surface and variograms indicated that anisotropic variogram was suitable for this analysis.

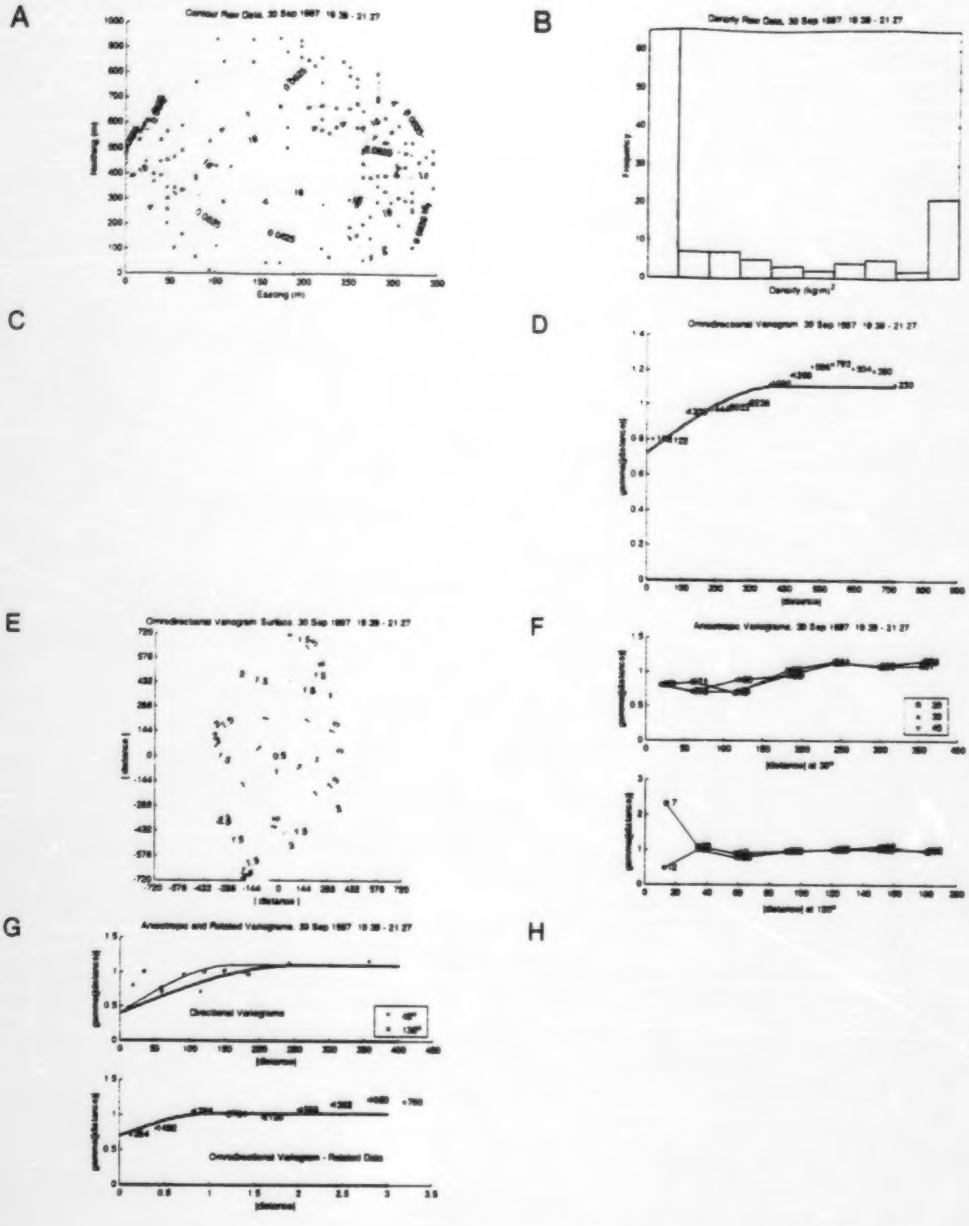


Fig. A1.26. Components for block kriging analysis for gillnetter data 30 Sep 1997, region 01, between 19.39 – 21.27. Variogram surface and variograms indicated that anisotropic variogram was suitable for this analysis.

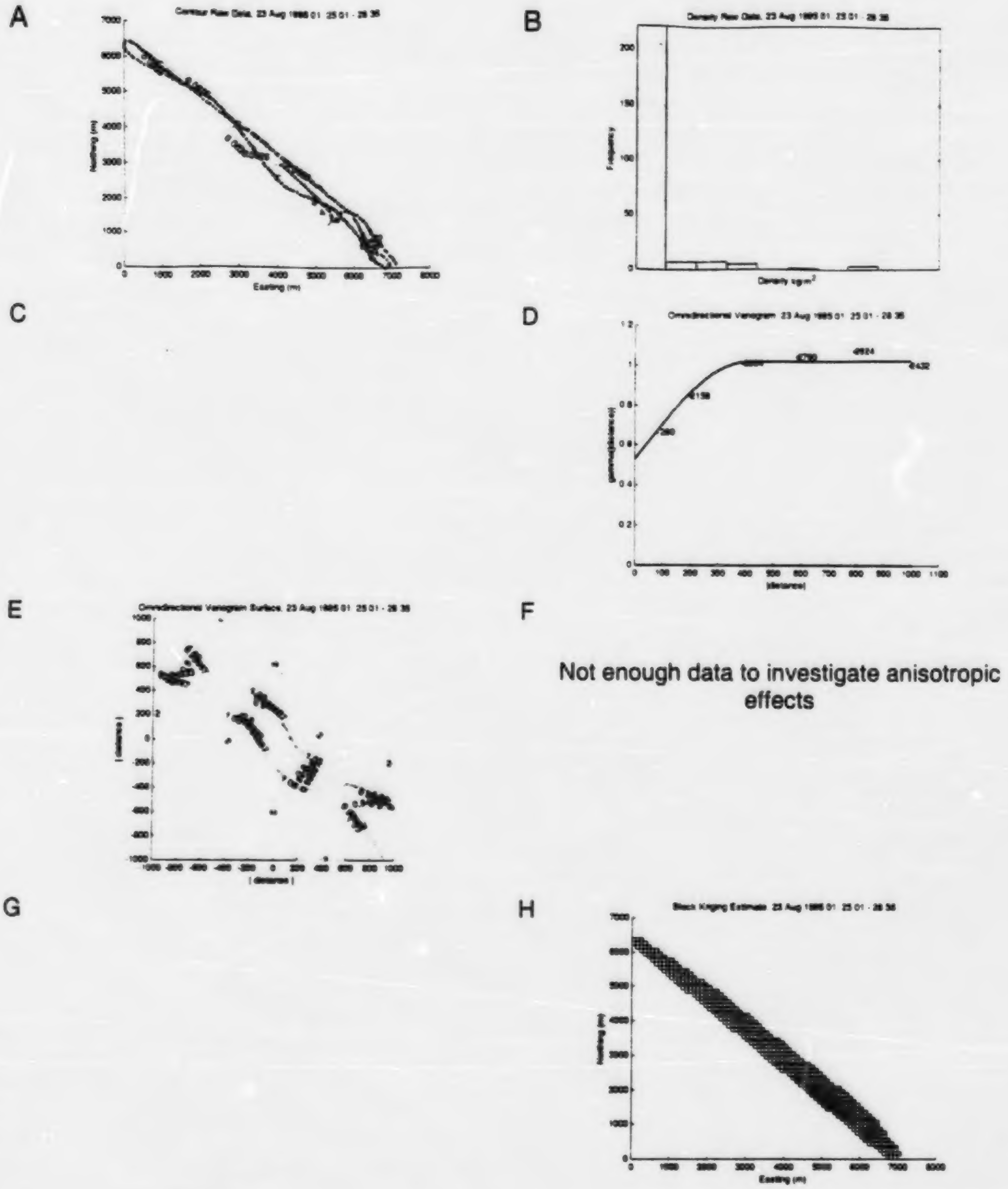


Fig. A1.27. Components for block kriging analysis for purse seiner data 23 August 1995, region 01, between 25.01 - 28.35. Variogram surface and variograms indicated that omnidirectional variogram was suitable for this analysis.

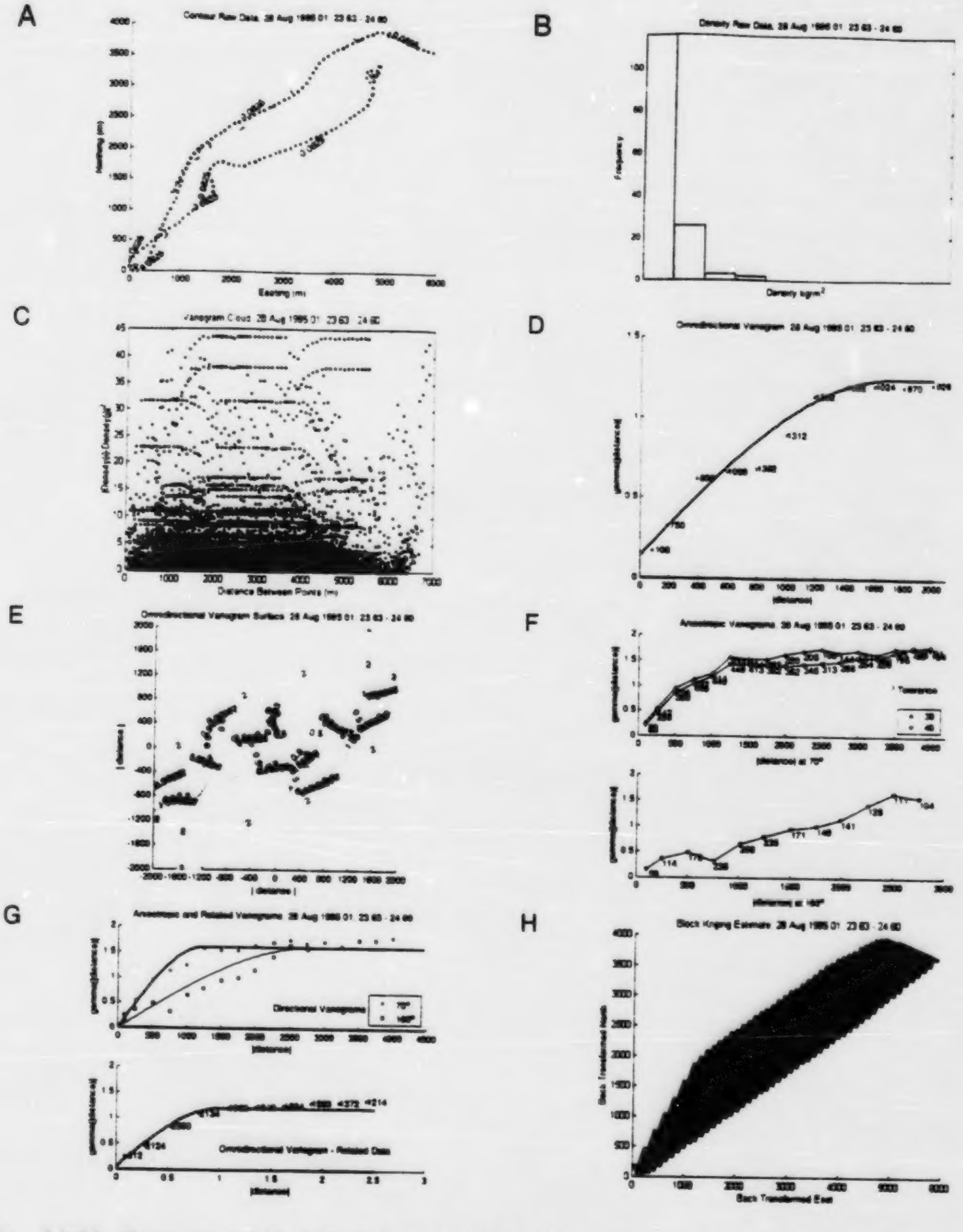


Fig. A1.28. Components for block kriging analysis for purse seiner data 28 August 1995, region 01, between 23.63 - 24.60. Variogram surface and variograms indicated that anisotropic variogram was suitable for this analysis.

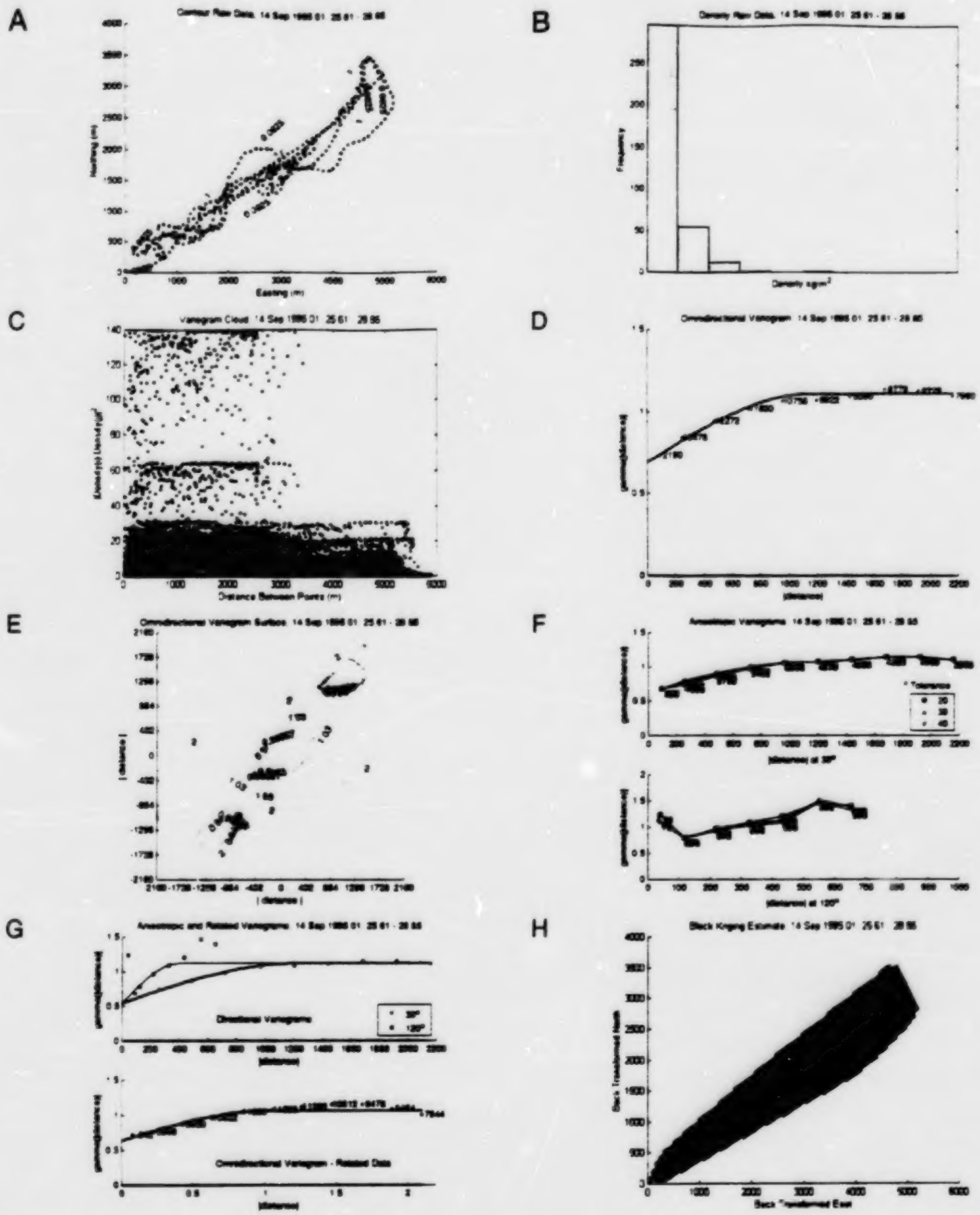


Fig. A1.29. Components for block kriging analysis for purse seiner data 14 September 1995, region 01, between 25.61 - 28.85. Variogram surface and variograms indicated that anisotropic variogram was suitable for this analysis.

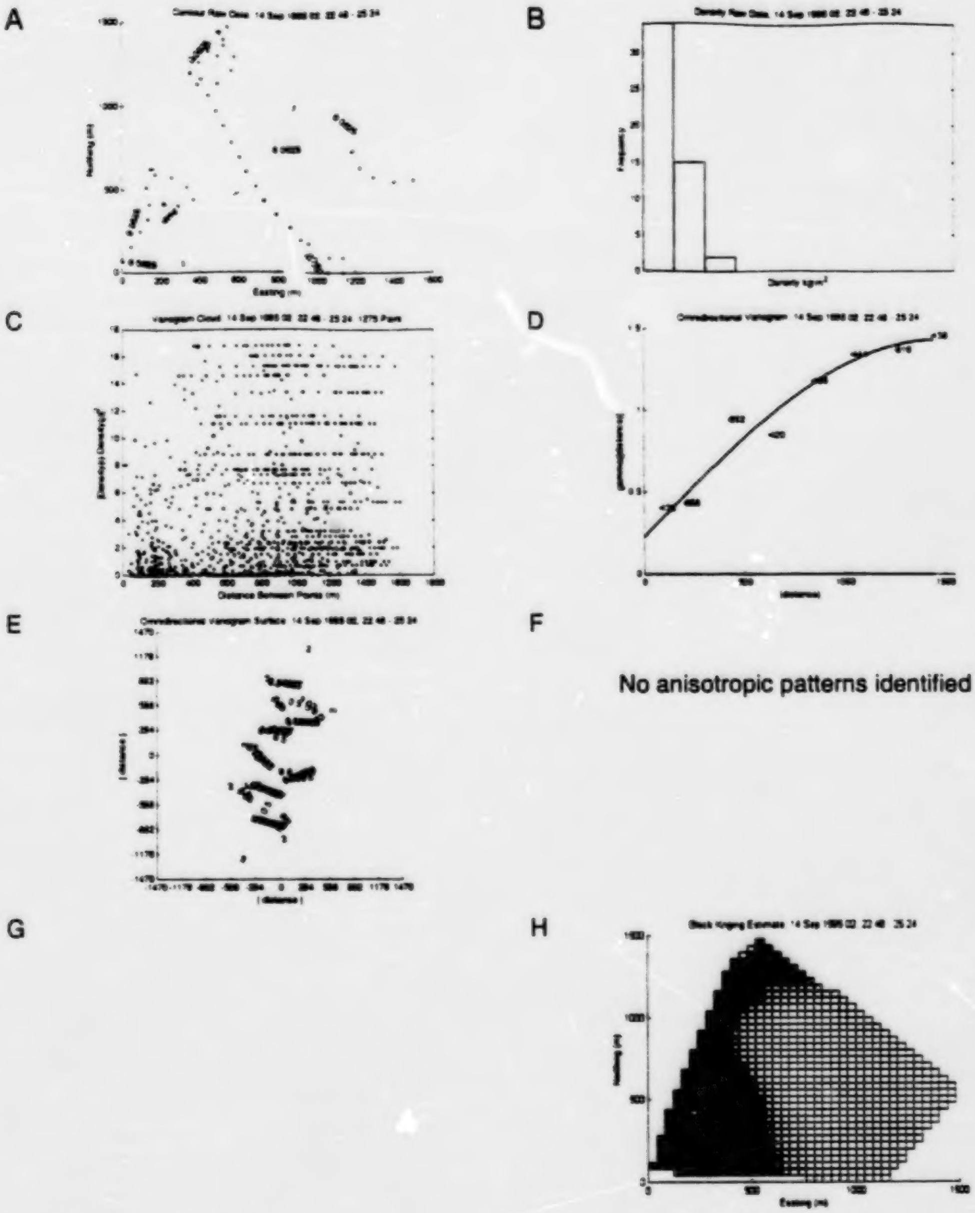


Fig. A1.30. Components for block kriging analysis for purse seiner data 14 September 1995, region 02, between 22.48 - 25.24. Variogram surface and variograms indicated that omnidirectional variogram was suitable for this analysis.

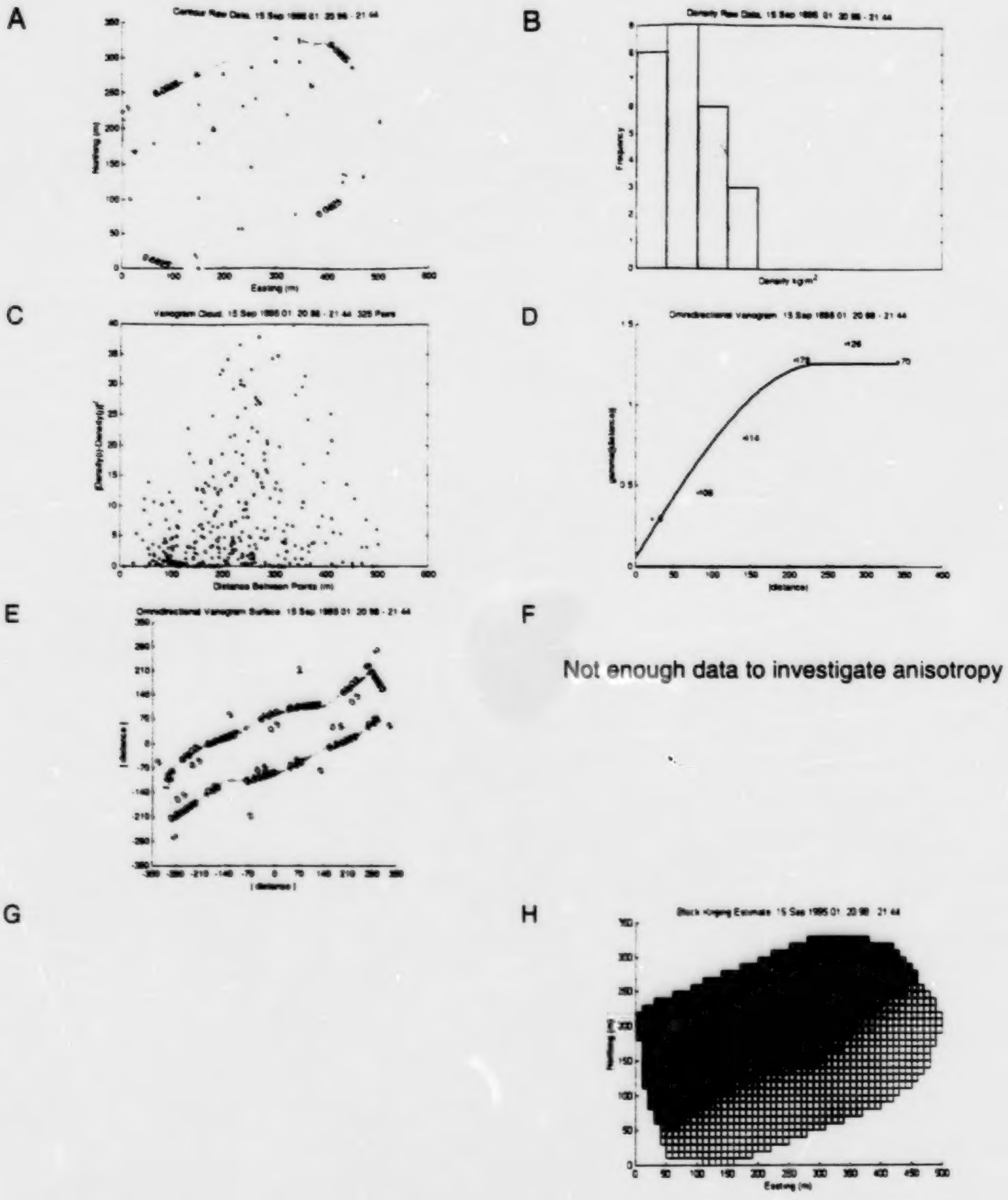


Fig. A1.31. Components for block kriging analysis for purse seiner data 15 September 1995, region 01, between 20.98 - 21.44.. Variogram surface and variograms indicated that omnidirectional variogram was suitable for this analysis.

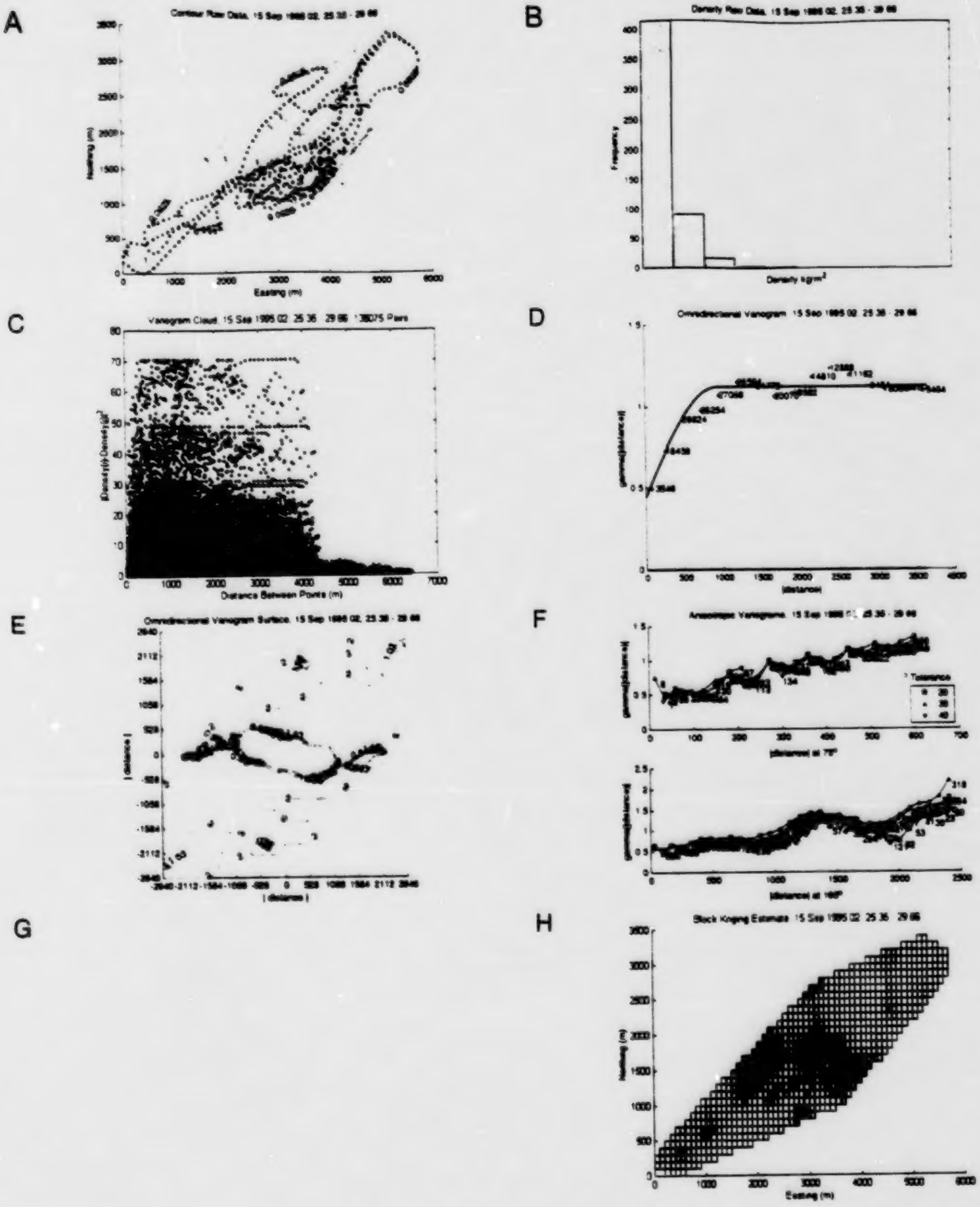


Fig. A1.32. Components for block kriging analysis for purse seiner data 15 September 1995, region 02, between 25.35 - 29.66. Variogram surface and variograms indicated that omnidirectional variogram was suitable for this analysis.

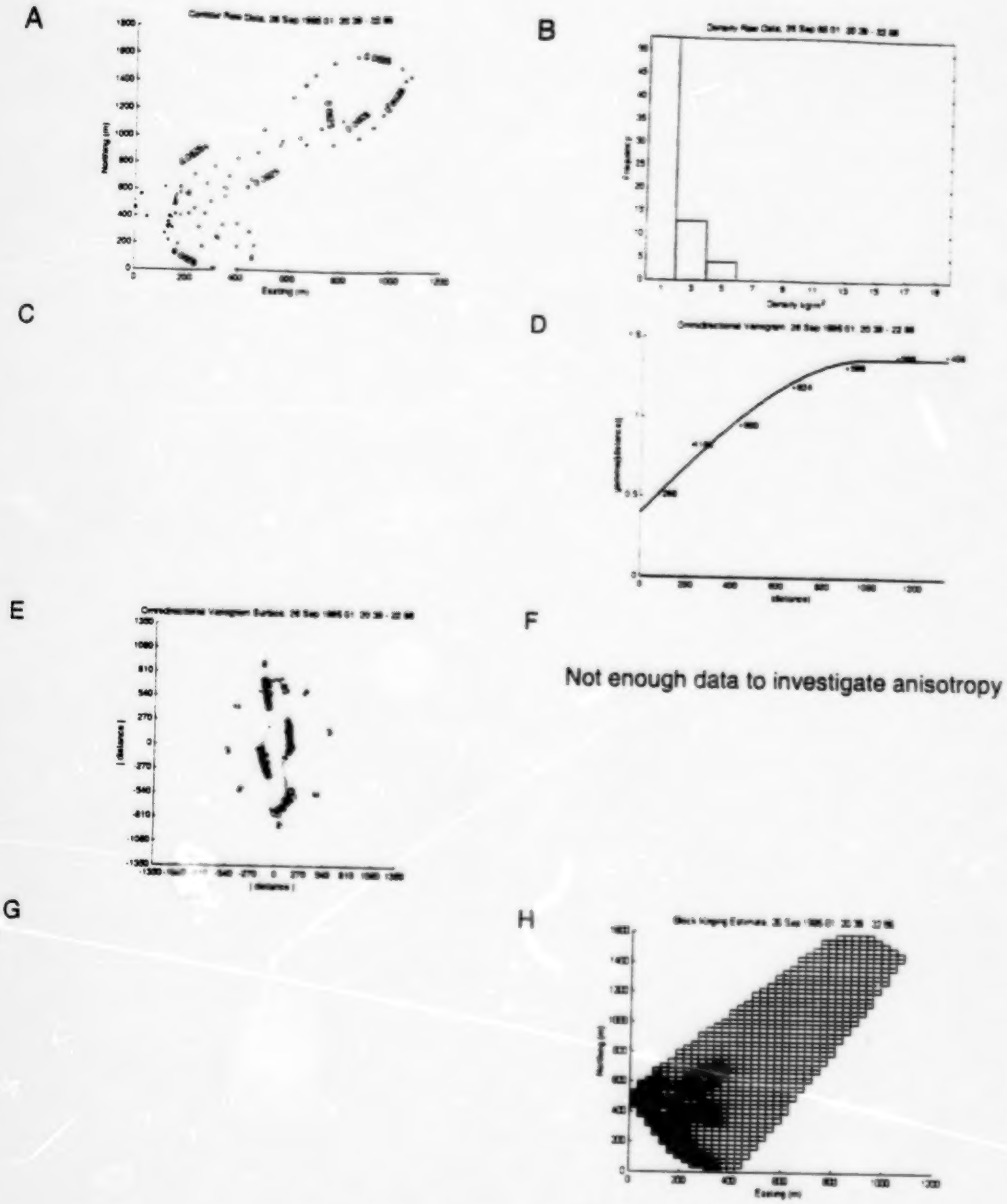


Fig. A1.33. Components for block kriging analysis for purse seiner data 26 September 1995, region 01, between 20.39 - 22.86. Variogram surface and variograms indicated that omnidirectional variogram was suitable for this analysis.

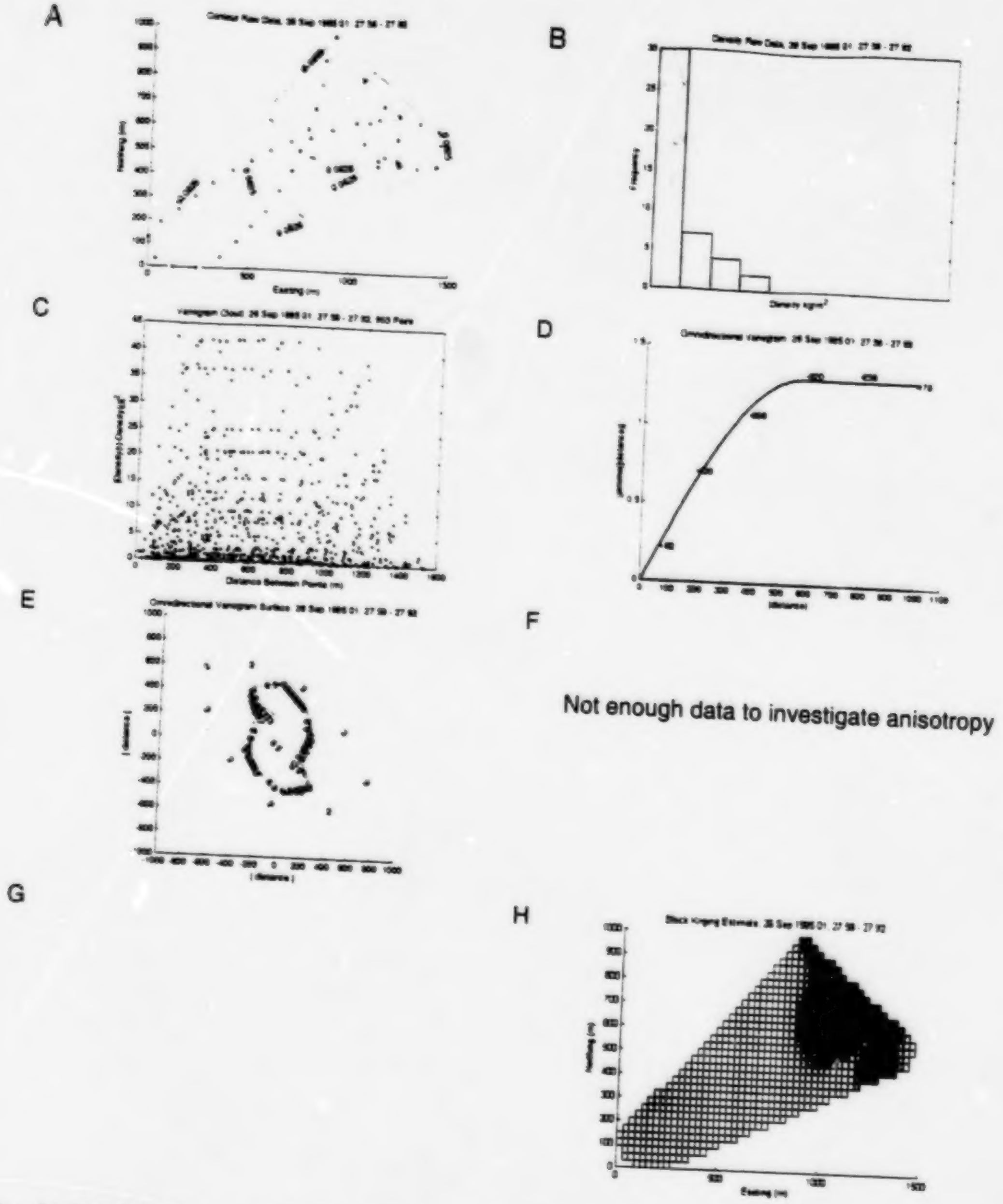


Fig. A1.34. Components for block kriging analysis for purse seiner data 26 September 1995, region 01, between 27.59 - 27.92. Variogram surface and variograms indicated that omnidirectional variogram was suitable for this analysis.

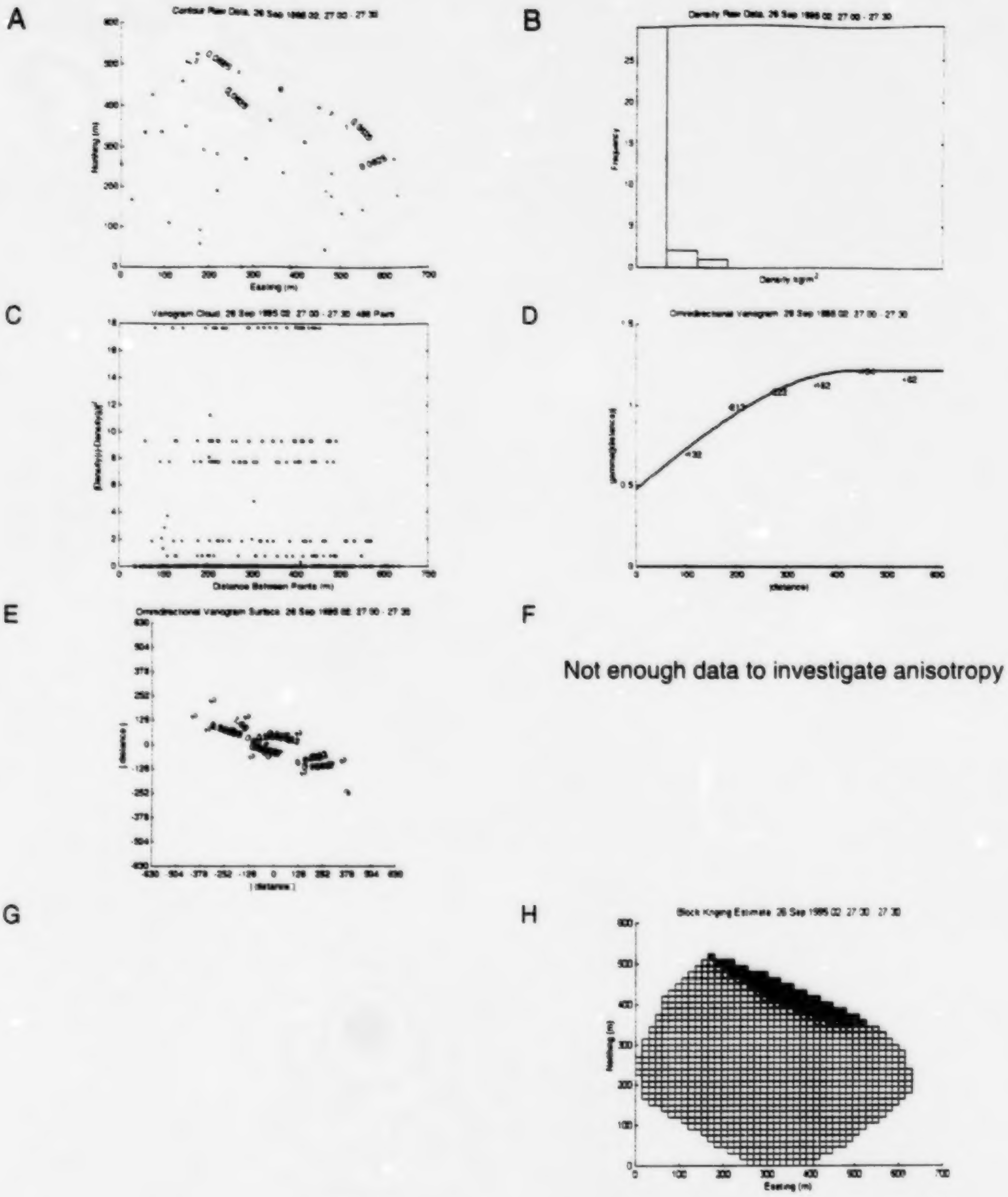


Fig. A1.35. Components for block kriging analysis for purse seiner data 26 September 1995, region 02, between 27.00 - 27.30. Variogram surface and variograms indicated that omnidirectional variogram was suitable for this analysis.

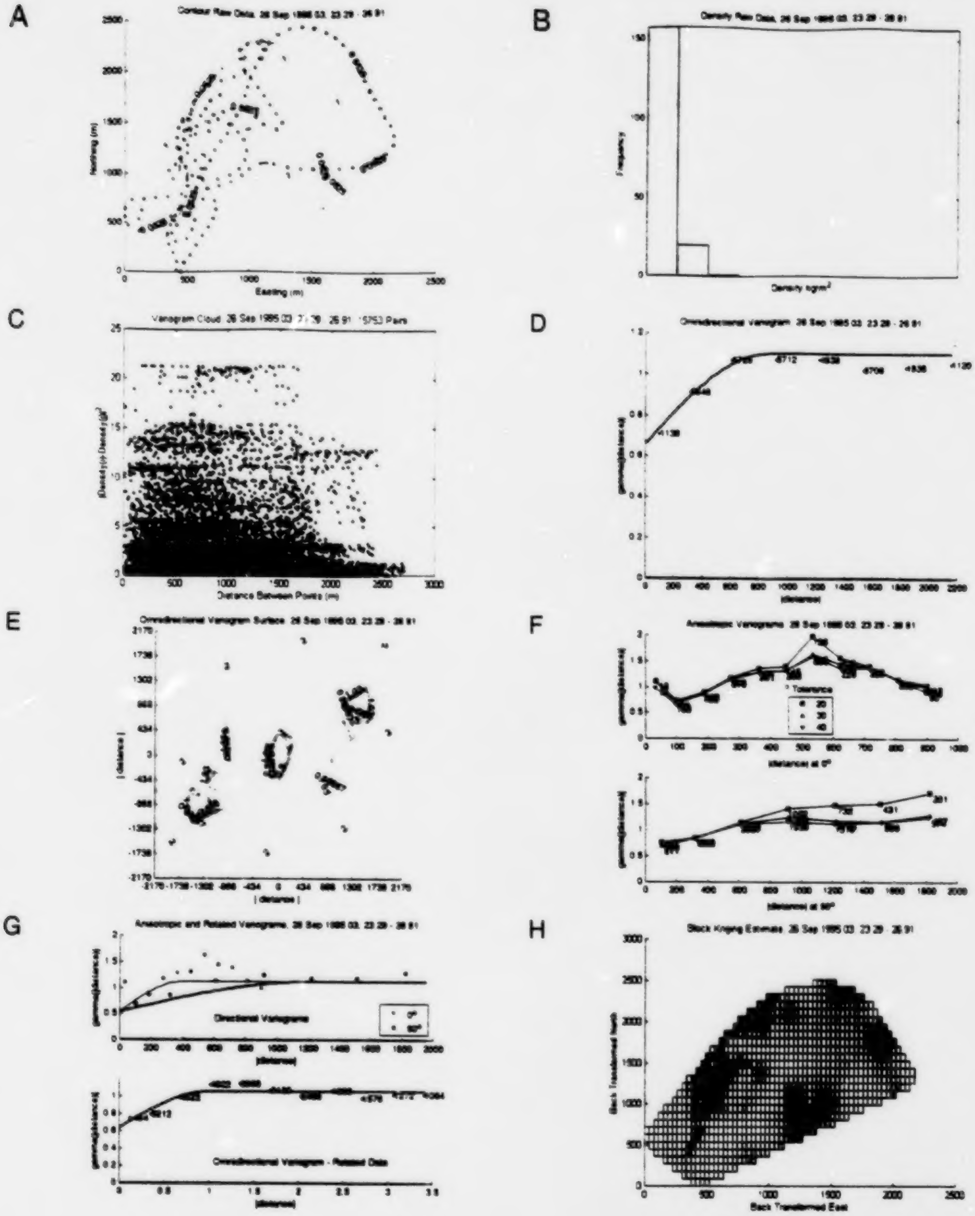


Fig. A1.36. Components for block kriging analysis for purse seiner data 26 September 1995, region 03, between 23.29 - 26.91. Variogram surface and variograms indicated that an anisotropic variogram was suitable for this analysis

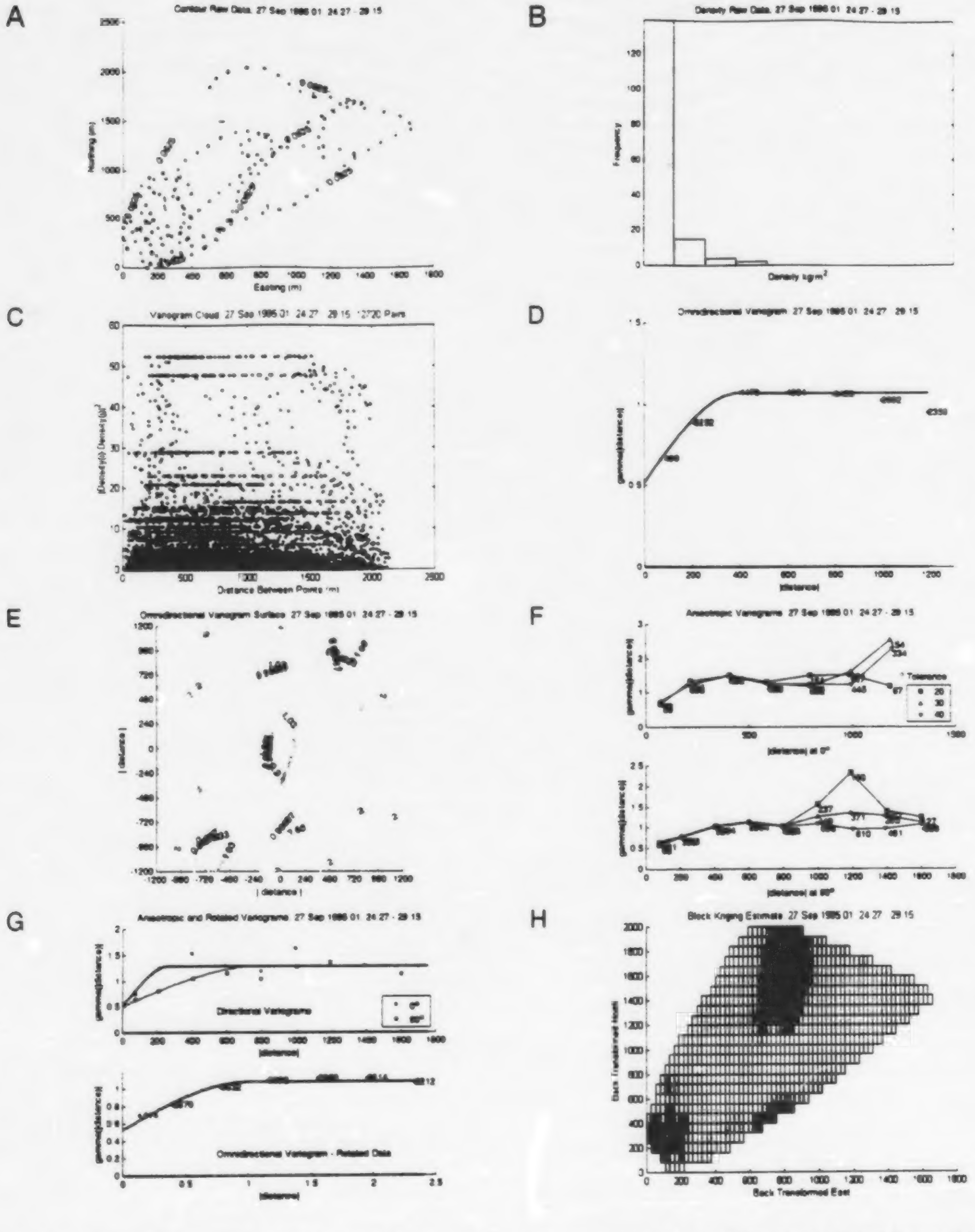
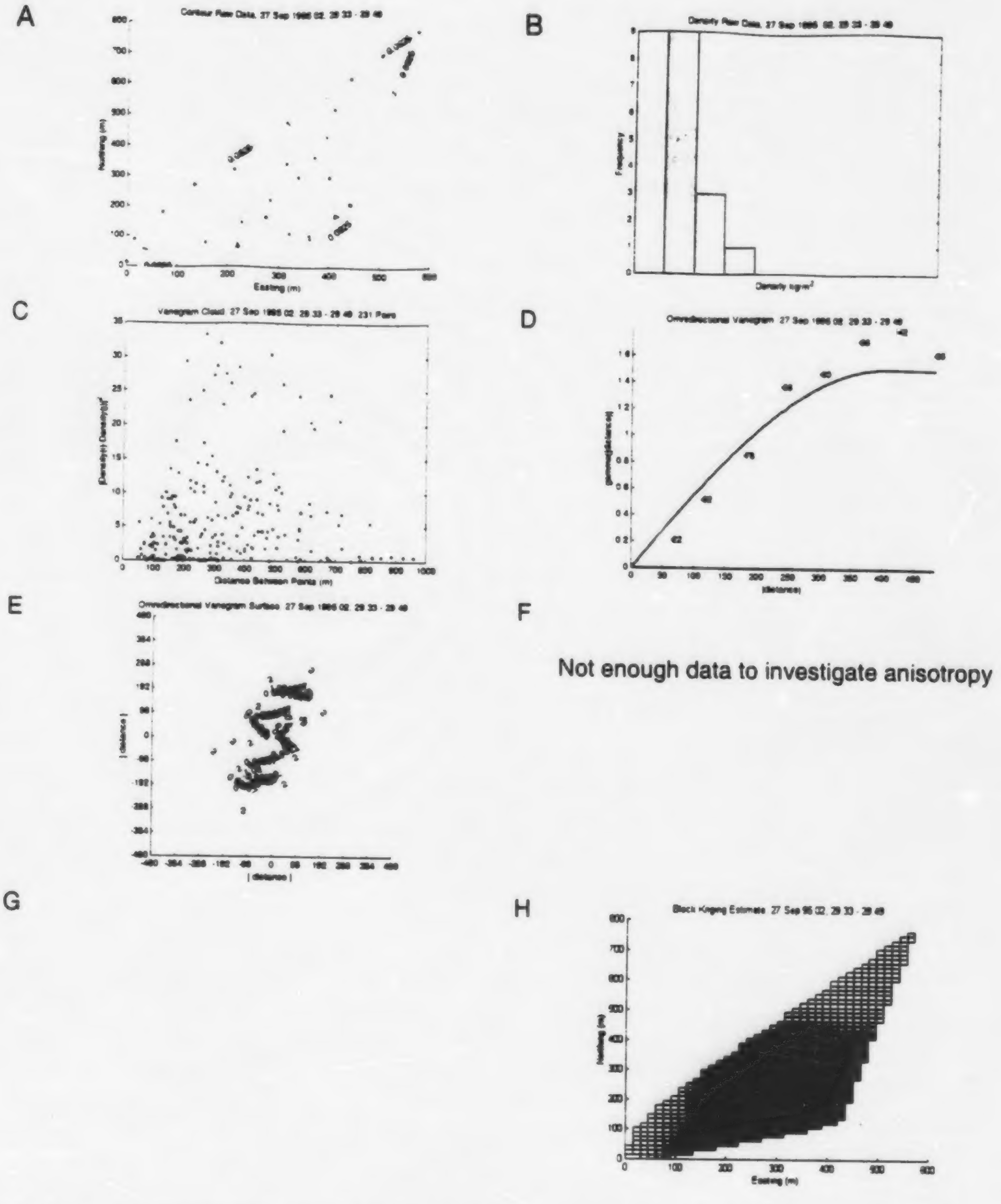


Fig. A1.37. Components for block kriging analysis for purse seiner data 27 September 1995, region 01, between 24.27 - 29.15. Variogram surface and variograms indicated that anisotropic variogram was suitable for this analysis.



Not enough data to investigate anisotropy

Fig. A1.38. Components for block kriging analysis for purse seiner data 27 September 1995, region 02, between 29.33 - 29.49. Variogram surface and variograms indicated that omnidirectional variogram was suitable for this analysis.

Appendix 2. Details for spatial simulation of stock structure and fishery.

A2.1 Stock structure

The number of clusters in the stock and the parameters defining each cluster determined the distribution type and biomass of the fish in the search area. Each cluster was defined by four parameters, (1) the centre point in the x axis and (2) the centre point in the y axis, (3) the biomass contained in the cluster, and by (4) the standard deviation. The density at each x,y coordinate was estimated as follows:

$$\rho = \frac{B}{\pi\sigma^2}\exp\left(\frac{-(x_i - x_c)^2 - (y_i - y_c)^2}{2\sigma^2}\right) \tag{A2.1}$$

where B = biomass, σ = standard deviation, x_i = datum point at location x, x_c = the centre of the distribution in the x axis, y_i = the datum point at the location y, y_c = the centre of the distribution in the y axis.

The parameters defining the five distributions examined are summarized below:

Distribution	Number of Centres	Standard Deviation	Scaling Factor (biomass)	Distance forced between centres (m)
Spiky	1	10	10	0
Intermediate between spiky and average (IAS)	3	20	3.3	40
Average	10	75	1	0
Intermediate between average and flat (IAF)	4	300	3.7	75
Flat	1	1000	265	0

The stock size was multiplied by the scaling factor during each simulation so that biomass within the search area would be equivalent across simulations.

Stock Sizes examined were:

[50 100 200 400 600 800 1000 1500 2000
2500 3000 4000 6000 8000 10000 15000] tonnes

A2.2 Stock and search area

The search area was a 700 metre square. The centres of the clusters were restricted to a 500 metre square in the centre of the search area (for examples see Fig. 42).

A2.3 Numerical Integration

Numerical integration was accomplished using the MATLAB (1998, ver 5.3) dblquad function. This function uses the adaptive recursive Newton-Cotes quadrature method for evaluating double integrals (Forsythe et al. 1977). Densities below 10^{-14} were excluded from the integration domain to avoid convergence problems. These cases occurred most often for spiky and intermediate between average and spiky distribution.

For a line segment such as a transect or fishing event, integration along the line was performed using the start and end points of the line as boundaries.

A2.4 Area containing 75% of biomass

Distribution types were quantified by determining the percentage of the search area that contained the mid 75% of the biomass as follows:

1. Divide the search area into grids 100 metres apart.
2. Determine the stock density at each grid point using equation (A2.1).
3. Determine the cumulative percentage of the density at the grid points, where the grid points are numbered by starting at row 1, column 1 and proceeding down each column by rows.
4. Determine the number of grid points between 12.5% and 87.5% and divide by the total number of grid points to determine the percentage of the area that contained 75% of the biomass.
5. Determine the average percentage for each distribution type.

For determining the cumulative distribution there was little difference between using grid points 100 metres apart and more closely spaced points. However, the time saved in computation was considerable and 100 metre grid points were used for this portion of the simulation.

A2.5 Fish movement

Fish movement was simulated by moving the centre of each cluster every five minutes of the simulated four hours allocated for searching and surveying. The distance and direction were determined as follows:

Parameter	Variable
Maximum cluster movement	200 metres
Direction	$2 \times \pi \times$ random number from a uniform distribution.
Distance of movement	Maximum cluster movement $\times$ random number from a
Change in x direction	Distance of movement $\times$ cos(Direction)
Change in y direction	Distance of movement $\times$ sin(Direction)

If the new centre of the cluster was outside the inner 500 metre square or if the centres were closer than the prescribed distance, another random selection was made until these conditions were satisfied.

A2.6 Turning direction while searching for fish

The rules governing the searching behaviour of the simulated acoustic boat were determined by the change in the density of fish observed over each 100 metre search increment. The change in fish density was determined by calculating the linear slope of density every 20 metres of the 100 metre search increment. At the end of the 100 metres a decision on turning angle and direction of the turn would be made according the following rules:

Slope	Turning Angle Range (degrees)
<-1	150 - 180
≥-1 and <-.5	120 - 150
≥-.5 and <0	90 - 120
≥0 and < .5	60 - 90
≥.5 and <1	30 - 60
≥1	0 - 30

The angle within each range and the direction as either a right or left hand turn were selected using uniform random number distributions.

A2.7 Criteria for fishing by simulated acoustic boat

The rules determining when and where the simulated acoustic boat fished were as follows:

Fish if:

If Catch < Boat Limit and

1. (Mean Density along 100 metre increment ≥ Astonishing Stock Density)
2. OR Mean Density along 100 metre increment ≥ High Local Density and Slope < Negative Slope at High Local Density)
3. OR (Number of Times in One Spot ≥ 7)
4. OR (Mean Density along 100 metre increment ≥ Low Local Density AND Time>Total Time / 2 AND Random Number (0 - 1) < Proportion of the fleet fishing).

If fishing takes place no simulated data is collected for 30 minutes.

The parameters used to define the fishing rules were as follows:

Parameter	Variable
Astonishing Stock Density	Maximum Observed Density *x* 0.95
High Local Density	Maximum Observed Density *x* 0.75
Low Local Density	Maximum Observed Density *x* 0.50
Negative Slope at High Local Density	-1 kg/m
Small Slope at Low Stock	0.05 kg/m
Number of times in one spot	Number of consecutive times that the slope changed from -0.1 kg/m to +0.1 kg/m while searching
Total Time	4 Hours, total of simulated searching and surveying time
Proportion of fleet fishing	Average number of acoustic boat trips / Number of fishing events possible for the fleet (see Fishing by fleet boats below)

A2.8 Acoustic boat catch

Catch by the acoustic boat was determined using the following relationship with parameters and variables as described below:

$$\text{Catch} = \text{Swept area} \times \text{Density} \times \text{Vulnerability} \qquad (A2.2)$$

Parameter	Variable
Swept area	Effective width of net *x* net length
Density	Density integrated over length of the net
Vulnerability	Proportion of fish biomass present that is caught by the net
Effective width of net	2.5
Net Length	150
Vulnerability	0.75

If the cumulative catch for the boat was $\leq$ Boat Limit (7500 kg) then the catch for that event was equal to catch calculated as above. If the cumulative catch for the boat was > Boat Limit then the catch for that event was equal to:

$$\text{Catch} = \text{Boat Limit} - \text{Previous cumulative catch} \tag{A2.3}$$

As a result, the cumulative catch for the acoustic boat could not exceed the nightly boat limit.

A2.9 Fleet fishing

The rules governing fishing by the fleet boats differed from those for the simulated acoustic boat. Only one boat was collecting acoustic simulated data for biomass estimation. There were two purposes for simulating fishing by the fleet. The first was to simulate the effects of depletion during the acoustic simulated data collection on proposed indices. The second was to compare the effectiveness of fleet and acoustic boat catch rates to the acoustic indices for stock assessment purposes. As a result, it was not necessary for each individual boat in the fleet to search according to the rules defined for the acoustic boat and considerable computation time was saved by considering when and where the fleet would fish as a group. The catch of each boat was recorded in a consistent sequence for each fishing event. This sequential fishing permitted the stock to be depleted gradually as the catch for each boat occurred and meant that the catch of each boat was dependent on the stock remaining when it was its turn to fish. This procedure was more realistic than one alternative which was to have all boats fish at once so that the catch of each boat depended only on the stock present at the beginning of the fishing event. Three factors were considered with respect to fleet fishing: number of boats fishing on a night, fishing locations of each boat, and the proportion of the boats fished during each fishing event.

A2.10 Number of boats fishing

Fleet size (number of boats fishing) was determined using the relationship between biomass and the number of boats fishing in the Pictou, 1997 gillnet fishery (Tables 6, 7). This relationship was:

$$\text{Fleet size} = 32 + 0.04\ x\ (\text{Stock Size} / 1000) + 10\ x\ \text{Random Normal Number} \tag{A2.4}$$

The minimum fleet size was 9 boats and the maximum fleet size was 119 plus one for the acoustic boat.

A2.11 Fleet fishing locations

Fishing locations for the fleet boats were selected to be consistent with vessels being able to locate higher than average densities for fishing. This objective was achieved by randomly selecting points from the cumulative distribution of densities in the search area as follows:

1. Determine stock density at grid points 10 metres apart.
2. Determine total stock by summing up grid point values.
3. Determine relative proportion of the stock at each grid point. Grid points are numbered across columns starting at column 1, row 1 of the grid matrix.
4. Determine relative stock at grid point by:

$$\text{Relative Stock at Grid Point}^{(\text{Random Number }(0.5\text{ to }1.5))} \tag{A2.5}$$

5. Determine the cumulative distribution of the relative proportion of the grid point densities.
6. Determine the point on the cumulative distribution that corresponds to a uniform random number selected for each fleet vessel.
7. Determine the fishing location by relating the point on the cumulative distribution back to the grid point location.

A2.12 Fishing by fleet boats

Determining the catch of fleet boats consisted of two steps. The first was determining the proportion of the fleet that fished during each fishing event. The second was determining the catch of each boat that fished.

A2.13 Determine the proportion of the fleet fishing each event.

1. Determine the average number of trips the acoustic boat will make at each stock distribution and size by running the simulation for three times.
2. Determine the proportion of the fleet fishing as:

Proportion of the fleet fishing = Average number of acoustic boat trips / Number of fishing events possible for the fleet (A2.6)

3. Determine the average number of acoustic boat trips made for each simulation at the given distribution and stock size by updating this figure after each trip.

A2.14 Determine catch of each fleet boat

1. Determine if vessel fishes (random number < proportion of fleet fishing).
2. Determine the vessel catch using same formula as for acoustic boat, equation A2.5.
3. Determine if the previous catch for this boat plus the current catch is less than the boat limit.
    3.1. If it is then add the catch for this boat,
    3.2. If it is not then take only that portion that brings the boat up to the boat limit.

A2.15 Deplete the stock by clusters

As fishing progressed the stock was depleted according to the proportion that each cluster contributed to the catch. For example, if most of the catch occurred near the centre of one distribution and the edge of another then the cluster that had the catch near its centre would have more biomass removed from it than the one where catches occurred near the edge. This applied for catches by the simulated acoustic boat and the fleet catches. The clusters were depleted as follows:

1) Determine the density in each cluster at the fishing location.
2) Determine the total density at the fishing location by summing the densities from each cluster.
3) Determine the proportion that each cluster contributes to the sum.
4) Determine the catch from each cluster according to the proportion in (3) and deduct it from the cluster.